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Effects of Delayed Drying and Storage Conditions on Milling, Color, and Viscosity Properties of Rice

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Milling, Color, and Viscosity Properties of Rice

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Abstract

Head rice yields (HRYs), kernel discoloration, and functional properties are three hallmarks of rice quality, and can be impacted after harvest by storage conditions. This study evaluated impacts on rice quality due to controlled storage at moisture contents (MCs), temperatures, and storage durations that may be incurred during Mid-South rice farming practices. Three hybrid, long-grain cultivars, harvested in Arkansas in 2014 and 2015, were stored in rough rice form at 4 MCs (12.5%, 16%, 19%, and 21%), and 5 temperatures (10°C, 15°C, 20°C, 27°C, and 40°C), for 16 weeks, with samples taken every 2 weeks. After drying and milling, HRYs, discoloration, and viscosity parameters were analyzed. All storage conditions maintained HRY for at least 12 weeks, but storage for 16 weeks at 21% MC and 27-40°C in 2014 led to large reductions in HRY; these samples also contained tremendous visible fungal growth. Discoloration, measured with an image analysis system calibrated for this study, was minimized by storage at 10-15°C and at MCs ≤19% for up to 16 weeks. Discoloration in samples stored at 20-40°C varied by cultivar and by year, with a unique pattern observed at 27°C and 21% MC in 2014. Storage at 10-15°C limited increases in peak viscosity during storage, but minimum breakdown and maximum setback were observed after 16 weeks of storage at 21% MC and 10°C. At 20-27°C, peak and final viscosities and breakdown initially increased over the storage duration, then leveled off after 8-12 weeks. At 40°C, peak viscosity and breakdown increased at first, then declined after 2-6 weeks, especially with increasing storage MCs. Final viscosities increased steadily with storage at 40°C, therefore setback increased substantially after 2-4 weeks. The results of this study support the implementation of grain cooling for HRY and color quality preservation, identify the conditions that may promote discoloration in natural-air

bin dryers, and suggest maximum temperatures and storage durations for aging hybrid, long-grain rice.

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Table of Contents

List of Tables

List of Figures

Abbreviations

cP – centipoise

D – storage duration

FGIS – Federal Grain Inspection Service

HRY – head rice yield

HSD – Honestly Significant Difference

LS – least square

MC – moisture content

NIR – near infrared reflectance

pp – percentage point

RVA – Rapid Visco Analyser

SLC – surface lipid content

T – temperature

USDA – United States Department of Agriculture

I. Introduction

Long-grain rice is harvested at moisture contents (MCs) above those needed for conventional storage practices in the Mid-South United States, at approximately 19-21% MC. Though harvesting at these higher MCs helps to minimize fissuring and breakage of kernels during drying and milling, it also creates circumstances that are associated with quality degradation, particularly kernel discoloration. The specific causes of discoloration are debated and not fully known, but are primarily related to MC and temperature. Additionally, moist grain is a breeding ground for fungi, which are associated with and may, to some degree, be responsible for kernel discoloration. A high-MC grain mass also respires, releasing energy that heats the kernels above ambient temperatures, possibly leading to further kernel discoloration that can cause the rice to be downgraded by USDA standards.

Because of these effects, freshly-harvested rice is either immediately parboiled, dried and milled, or dried and stored to be parboiled or milled later. Because parboiling facilities operate year-round, only a fraction of fresh rice can be parboiled. But rice that is dried prior to parboiling is also dried afterwards. Drying is an expensive process, so it may be beneficial to be able to store the fresh rice under cooling conditions until parboiling. Yet drying and storing rice for 2-3 months is associated with changes in functionality, such as an increase in water-holding capacity and formation of a more ordered arrangement of starch that is more stable to shear stress. These aging effects may be desired depending on intended processing fate and final product attributes. Cooling generally retards these aging effects, but the extent to which cool temperatures impede aging needs to be quantified. And yet, cooling promises numerous benefits, such as preservation of HRYs and kernel color, and reduction of fungal and insect growth, prompting the need to determine the impact of various cooling temperatures on rice at a range of MCs.

This study evaluates the effect of storage conditions on long-grain rice quality, particularly HRY, kernel discoloration, and functional properties. The experiments were designed to imitate storage for up to four months with a range of ambient temperature conditions, and with cooling. Storage MCs were chosen to encompass a range typical to Mid-South harvesting and drying practices.

A unique method of quantifying discoloration was devised for this study, and multiple regression analyses were employed so that the effects of storage conditions could be evaluated across a spectrum of MCs, temperatures, and storage durations. Though the study was conducted as one large project, for clarity, the data were segmented into two sets: storage at low to high ambient temperature conditions—which will be addressed first to explain detrimental effects occurring in high-MC regions of natural-air bin dryers—and storage at cool to low ambient conditions, which will follow to suggest a potential solution for ensuring quality.

II. Rice Quality Impacts Due to Simulated Delayed Drying of Rough Rice at Harvest Moisture Contents under High Ambient Temperature Conditions

A. Abstract

In-bin, on-farm drying systems, utilized across the Mid-South rice-growing region, offer convenience to farmers, but by design can present challenges for maintaining kernel quality under certain ambient air conditions during the drying period. Under rainy or high-humidity conditions, drying fronts are often stalled, such that the top layer of rice may maintain its harvest moisture content (MC) for many weeks. This high MC level, in addition to warm ambient temperatures in early autumn, creates ideal conditions for fungal growth, kernel discoloration, and functionality changes. This study evaluates the effects of rough rice storage at MCs of 12.5%, 16%, 19%, and 21% for up to 16 weeks at temperatures of 20°C, 27°C, and 40°C on milling yields, kernel color, and functionality characteristics of three long-grain cultivars. Head rice yield was negatively impacted by high-MC, high-temperature storage, but only after other significant quality reductions had taken place. Temperature-specific discoloration patterns were observed at 27°C and 40°C in 2014; though similar discoloration was observed at 40°C in 2015, the unique variegated pattern in samples stored at 27°C was absent. This year-to-year variability in susceptibility to post-harvest kernel discoloration implicated unknown pre-harvest factors. Peak viscosity, breakdown, and final viscosity tended to increase over the storage duration at 20°C and 27°C and all storage MCs, but leveled off after 8 weeks. Storage of rice at all MCs at 40°C greatly reduced peak viscosity after 6 weeks. These results provide upper limits of MC, temperature, and storage duration for preventing quality losses with in-bin dryers, and may guide future research into the effects of pre-harvest factors on kernel discoloration.

B. Introduction

In the Mid-South United States, long-grain rice cultivars are harvested at around 19-21% moisture content (MC)[1] for optimum head rice yields (HRYs). This moist, fresh grain provides a perfect medium for fungi to grow and thrive in the warm post-harvest climate typical to rice-growing regions (Sahay and Gangopadhyay, 1985). Under certain conditions, fungi can produce dangerous mycotoxins (Magan et al., 2003). The same circumstances that promote fungal growth are also associated with post-harvest discoloration of rice kernels. There is considerable debate about whether fungal growth causes discoloration, or whether fungal growth and discolored pigments develop simultaneously, but independently; yet prevention of both is of critical importance to rice farmers and processors.

Storage of rough rice to prevent mycotoxin development and maintain quality therefore typically requires drying to reduce moisture content (MC) and thus water activity in the grain to sufficiently low levels to minimize respiration and fungal growth. This can be accomplished through commercial or on-farm dryers that quickly dry rice with several passes of heated, dry air (Schluterman and Siebenmorgen, 2004). In recent years, however, natural-air, in-bin drying systems have been widely implemented in the Mid-South (Lawrence et al., 2015). In-bin drying is accomplished by passing ambient or conditioned air through a perforated floor of a rice bin, drying the moist grain from the bottom up. As the drying front moves through the grain mass, the rice closest to the floor may be over-dried, while the top layer of rice often remains at a high MC. This top layer of rice is most susceptible to fungal growth and discoloration.

The Federal Grain Inspection Service (FGIS) of the United States Department of Agriculture Grain Inspection, Packers and Stockyards Administration assigns grades to rice

[1] All moisture contents are given on a wet-basis.

based on the number of discolored or otherwise unacceptable kernels in a sample. U.S. No. 1 grade milled rice may contain, at maximum, only one heat-damaged kernel per 500-g sample (USDA, 2009). The FGIS maintains reference photos of heat-damaged kernels, called interpretive line slides, which graders use to evaluate samples. This low threshold can have a large impact on farmers' profits if their rice exceeds the number of heat-damaged kernels permitted. The fact that grading depends on a human operator comparing kernels to a photo also makes the system somewhat subjective and less than ideal for maintaining uniform standards.

Some pre-harvest, pre-storage causes of discoloration are well-known. Insects, such as the rice stink bug, fungal pathogens, such as the *Curvularia* species that cause black kernel disease, and panicle submergence during grain development all contribute to discoloration prior to storage (Misra et al., 1994; Mettananda et al., 2000; Lorenz and Hardke, 2013). But the causes of discoloration during storage are not as well-understood, and are often contested. Fungi are an obvious choice to blame for discoloration; they thrive in high-moisture and moderate-temperature conditions when discoloration is developing. Therefore, fungi are favored as the true cause of discoloration by some researchers, such as Schroeder (1964, 1965), who found that inoculating sterile kernels with *Fusarium chlamydosporium* and incubating at 22% MC and 30°C for 10 days led to significant increases in brown and black pigmentation, especially after parboiling, as compared to sterile, un-inoculated kernels. However, Schroeder (1963) had previously found no correlation between overall prevalence of fungi and the extent of discoloration. A study by Phillips et al. (1988) also did not document such a correlation.

Other researchers argue that the assumption that fungi cause discoloration is ill-conceived. Bason et al. (1990) found that yellow kernel discoloration occurs at high temperatures (60°C) and low water activities (a_w=0.40, 0.60), conditions that would inactivate fungi. Belefant-

Miller et al. (2005) observed that discoloration penetrates the endosperm, but fungal hyphae were not found within the endosperm of yellowed samples. Also, yellowing was induced in fungus-free endosperm from rice plants grown from fungicide-treated seed and sprayed with fungicide during development. However, Belefant-Miller et al. (2005) used 5-day incubations at the longest, MCs below 14%, and temperatures of 61.5°C to 81.6°C. These results, therefore, cannot entirely discredit the idea that storage for several weeks, at harvest MCs of 19-21%, and 20-40°C ambient temperatures, could allow fungal interactions to affect discoloration. In fact, Bason et al. (1990) hypothesized that discoloration could arise from fungal and non-fungal sources when the model produced by their experimental results predicted much lower yellowing rates than were actually observed at high water activities.

Temperature and MC are the two most important factors associated with rice quality impacts during storage. With a fixed storage temperature of 25°C, Trigo-Stockli and Pederson (1994) found that increasing rough rice MC, up to 26%, lead to increased kernel discoloration and reduced milling yields over a 30-day storage duration; fungal growth also generally increased with increasing MC. Since respiration releases energy, elevated MCs increase the effective temperature experienced by stored grain. Trigo-Stockli and Pederson therefore also observed that respiration induced a maximum effective temperature of 63°C in rice stored at 26% MC. Milling yields also decreased with increasing storage duration, MC, and temperature. However, it has been noted by Houston et al. (1957) that milling yields do not decrease until overall quality has suffered.

Respiration by both the grain and associated microbes depletes oxygen while producing excess carbon dioxide, water, and energy. Storage MCs up to 25% and temperatures up to 60°C increased respiration rates in long-grain, pure-line cultivars (Dillahunty et al., 2000). Increased respiration is associated with many deleterious effects on rice, including dry-matter loss and kernel discoloration (Smith and Dilday, 2003). Oxygen and carbon dioxide levels, though intimately related to respiration, do not appear to affect kernel discoloration on their own, however (Bason et al., 1990). Degradation associated with respiration is typically prevented by drying rice to approximately 12-13% before storage, drastically reducing respiration.

Discoloration presenting as yellow pigmentation in rice endosperm can be induced in rough, brown, and milled rice by high-temperature (52-70°C) stress (Bason et al., 1990; Dillahunty et al., 2001; Belefant-Miller et al., 2005; Belefant-Miller, 2009; Ambardekar and Siebenmorgen, 2012; Bryant et al., 2013; Belefant-Miller and Grunden, 2014). Temperatures of 70°C also lead to discoloration in isolated rice bran in Belefant-Miller and Grunden's (2014) study, and this discoloration was associated with an increase in total carotenoid content, suggesting that the enzymes responsible for carotenogenesis are more active at high temperatures and may be responsible for the associated yellow pigmentation. However, because the study used rice bran rather than brown or rough rice kernels, it is not clear if in a whole-grain storage scenario the carotenoids would be synthesized in the bran and penetrate the endosperm where the yellow pigment can be found throughout. The difficulty of chromatographically separating colored pigments for analysis has hindered research into mechanisms of discoloration (Schroeder, 1965).

Storage also alters physicochemical properties of rice. Peak viscosity tends to increase during long-term storage (up to 51 months) of dried (12-14% MC) rough rice at room temperature (Sowbhagya and Bhattacharya, 2001). Increasing storage temperature also increases peak viscosity during storage (Patindol et al., 2005). Perdon et al. (1997) found that peak viscosity initially increased during storage of dried rice at 20°C and 37°C, but leveled off 3 months into the 6-month storage duration. Setback increased during storage, along with pasting temperature and peak time, which are the temperature at which viscosity begins to develop and the duration required for the slurry to reach peak viscosity during analysis, respectively. Patindol et al. (2005) also observed pasting temperature increased over a 9-month storage duration, especially at 38°C, and that breakdown increased during storage at 4°C and 21°C, but decreased at 38°C. This decrease in breakdown at 38°C, and the gradual decrease in breakdown reported at 20°C, 30°C, and 40°C by Kanlayakrit and Maweang (2004) indicate that starch becomes more stable to shear stress during storage at elevated temperatures. Aging effects are accelerated by increasing storage temperature up to 37°C and storage MC up to about 14% (Swamy et al., 1978; Kumar and Ali, 1991; Pearce and Marks, 2001).

Several changes to rice components associated with aging have been described. Starch fine structure is altered during storage at 38°C, and to a lesser extent at 21°C; these alterations include a decreased amylose-to-amylopectin ratio, shortened average amylopectin chain length, and an overall shift in chain length distribution to shorter chains (Patindol et al., 2005). Proteins and lipids are likely involved in overall aging effects because these effects on viscosity are altered or not apparent in isolated starch (Teo et al., 2000; Zhou et al., 2002, 2003; Patindol et al., 2005). Enzyme activity generally changes significantly during storage, with amylase activity in particular decreasing over time (Chrastil, 1990; Dhaliwal et al., 1991). However, Desikachar and Subramanyan (1960) favor physical changes as the true causes of aging effects rather than a reduction in amylase activity because supplementing aged rice with amylase did not alter cooking quality.

This study evaluates the individual and interactive effects of rough rice storage MC, temperature, and duration on rice quality, and is differentiated from previous storage research primarily by its emphasis on imitating MC and temperature conditions in the top layer of drying bins in the Mid-South. Therefore storage temperatures will not be as high as the 52-70°C range used in other discoloration studies, because even increased temperatures above ambient conditions due to respiration would not be expected to exceed 50°C in long-grain, rough rice harvested at 19% MC (Trigo-Stockli and Pedersen, 1994). This study also introduces a new system for quantifying discoloration that could be considered a viable alternative to subjective grading systems currently in use.

C. Materials and Methods

Four lots of hybrid, long-grain rice were used in this study; all lots were harvested at approximately 22% MC. Two lots were obtained in 2014—cultivar XL753 from the University of Arkansas Northeast Rice Research and Extension Center near Keiser, AR, and CL XL745 from Running Lake Farms in Pocahontas, AR—and two lots in 2015—XP760 from Running Lake Farms and CL XL745 from another farm in Pocahontas. The rice from each lot was cleaned with a dockage tester (Model XT4, Carter-Day, Minneapolis, MN) immediately after harvest, and temporarily stored in a walk-in cooler at 4°C before being spread on tarps for conditioning to four MCs: 12.5%, 16%, 19%, and 21%, representing a fully-dried control, and low, medium, and high harvest MCs, respectively. After the rice on each tarp had reached the desired MC according to a moisture meter (AM 5200, Perten Instruments, Hägersten, Sweden), the MC was verified by drying two, 15-g samples in a 130°C oven (1370FM, Sheldon Mfg. Inc., Cornelus, OR) for 24 h (Jindal and Siebenmorgen, 1987), and a 0-week sample was taken for analysis. The remaining rice was distributed among labeled quart (0.95 L) glass Mason jars and sealed.

To imitate storage in Mid-South grain bins, three temperatures were chosen: 20°C, 27°C, and 40°C. Two storage units were maintained at 20°C and 27°C by relative humidity- and temperature-control units (AA5582, Parameter Generation and Control, Inc., Black Mountain, NC), while an incubator was used for the 40°C unit (BF720, BINDER Inc., Bohemia, NY). The jars of rice were placed inside the storage units, and two temperature sensors (HOBO Pro v2, Onset Computer Corp., Bourne, MA) were placed within each unit to verify maintenance of the storage temperature throughout the storage duration. One jar of each cultivar/MC/temperature combination was removed when each storage duration had elapsed. Selected durations were 2, 4, 6, 8, 10, 12, and 16 weeks, such that there were 56 jars (2 cultivars x 4 MCs x 7 storage durations) in each storage unit, for a total of 168 jars of rice for analysis each year. Storage conditions are summarized in Table 1.

When each jar was removed from storage, the MC of the rice was measured by drying duplicate, 15-g samples in a 130°C oven, and the remaining rice was dried on a metal screen in a chamber with air conditions maintained at 27°C and 60% relative humidity by a temperature- and relative humidity-control unit (AA5582, Parameter Generation and Control, Inc., Black Mountain, NC) to 12.5%. Two, 150-g sub-samples from each dried sample were dehulled with an impeller husker (Model FC2K, Yamamoto, Yamagata, Japan), then milled with a laboratory mill (McGill No. 2, RAPSCO, Brookshire, TX) having a 1.5-kg mass placed on the lever arm, 15 cm from the centerline of the milling compartment. Milling durations were selected for each cultivar to attain a head rice surface lipid content (SLC) of 0.4% as measured by near infrared reflectance (NIR) spectroscopy (DA 7200, Perten instruments, SE-141 05 Huddinge, Sweden). Durations were 17 s for XL753 and 22 s for CL XL745 in 2014, while in 2015, durations were 32 s for XP760 and 34 s for CL XL745.

After milling, the sub-samples were aspirated to remove excess bran, and separated into head rice—whole kernels and broken kernels at least ¾ the length of a whole kernel—and broken pieces with a sizing device (Model 61, Grain Machinery Manufacturing Corp., Miami, FL). Head rice yield was expressed as a mass percentage of the initial rough rice sample remaining as head rice. To verify expected SLC, and to estimate bulk discoloration on the L*a*b* color scale, each sub-sample was subjected to NIR spectroscopy. Approximately 50 g of head rice were poured into a black sample container; the surface was leveled, and the cup was placed on the rotating platform of the spectrophotometer. Two estimates were recorded for each sample, with the container being rotated automatically between spectrophotometric readings; the two estimates of SLC and L*a*b* values were automatically averaged by the software.

Because the bulk estimate of color did not adequately account for kernel-to-kernel variability, an image analysis system (WinSEEDLE Pro 2005a™, Regent Instruments Inc., Sainte-Foy, Quebec, Canada) was used to quantify the relative amounts of specific kernel colors. The software was calibrated with discolored kernels of interest from this study. Seven representative, non-white kernels, and two white kernels—one translucent and one opaque/chalky—were selected and arranged on a 32 mm-thick, clear acrylic tray (152 mm x 100 mm x 20 mm), then placed on a scanner bed with a blue plastic background and imaged. A crosshair tool in the software was used to select the desired colors for measurement from within the projected area of each kernel. The specific decimal codes of the red, green, and blue values of each color were saved to create an analysis profile. The specific colors in the profile were selected and defined as follows: translucent white, opaque white, three shades of yellow, red/brown, black/brown, pink/red, and light pink.

For kernel-to-kernel color analysis, approximately 100 head rice kernels from one sub-sample—the second sub-samples produced from each jar were not analyzed—were arranged on the acrylic tray, and scanned with the same blue plastic background that was used to create the analysis profile. The software analyzed the area of each of the 100 kernels in the resulting image and determined, by a pixel-by-pixel assessment, the percent of the 100-kernel projected area that was occupied by specific colors from the profile. The sum of the areas of each of seven discolored descriptors was considered the total projected, discolored kernel area for the sub-sample. The white or non-discolored areas of the 100 kernels were represented by the sum of the translucent and opaque white areas. Two repetitions from one sub-sample produced from each jar of rice were scanned and the results averaged.

To determine the effects of storage conditions on functional properties, a 15-g portion from one head rice sub-sample was ground into flour with a cyclone mill (3010-30, UDY, Fort Collins, CO) and subjected to viscosity analysis. The MC of the rice was first measured by drying a 2.5-g portion in a 130°C oven for one h. Approximately 3 g of flour were combined with 25 mL of deionized water in an aluminum cylinder, with exact quantities depending on the flour MC. The flour and water were mixed briefly with a plastic paddle, forming a slurry, before the sample cylinder and paddle were inserted into the viscometer (RVA Super 4, Newport Scientific, Warriewood, Australia). The slurry was first heated to 50°C and held at that temperature for 1.5 min, before heating at a rate of 12°C/min to 95°C, holding for 2.5 min, then cooling to 50°C at a rate of 12°C/min, while stirring and measuring viscosity continuously. A thermogram was produced by the viscometer software showing change in viscosity over the cycle duration, as well as summary statistics of peak viscosity, trough viscosity, breakdown (peak-trough viscosity), final viscosity, setback (final-peak viscosity), peak time, and pasting temperature.

Storage temperature, MC, and duration were fit as continuous variables in a multiple regression analysis platform (JMP Pro release 12.0.1, SAS Institute Inc., Cary, NC). The MC measured after storage from each jar of rice was used for each observation rather than the initial bulk MC after conditioning. The cultivar and harvest year were combined to form a single categorical variable with four levels: XL753-2014, CL XL745-2014, CL XL745-2015, and XP760-2015. The responses analyzed were HRY, discoloration, and viscosity properties. All interactions among the storage variables were considered in the initial model, as well as polynomial terms when appropriate, then non-significant ($\alpha>0.05$) terms were removed manually by backwards elimination unless they were contained in significant, higher-order effects. The least square (LS) means of responses for each cultivar-year were compared by Tukey's Honestly Significant Difference (HSD) test.

D. Results and Discussion

<u>Head rice yield</u>

Head rice yield varied significantly among cultivars and between harvest years (Table 2). Cultivar XL753 was excluded from analysis due to low HRYs in rice conditioned to 19% and 12.5% that were not caused by storage conditions. There was a significant negative effect on HRY due to MC in interaction with storage duration (regression analysis not shown), but this only occurred due to extremely low HRYs of CL XL745 stored at 21% MC for 16 weeks at 27°C and 40°C in 2014 (Figure 1). The rough rice stored under these conditions was covered in visible mold, which had likely infiltrated the kernels and apparently weakened many kernels, causing fracturing during the milling process. After excluding samples stored for 16 weeks from analysis, no storage conditions were shown to have significant effects on HRY. Head rice yield should therefore not be affected by storage at MCs up to 21% and temperatures up to 40°C until other qualities have suffered, consistent with findings from Houston et al. (1957).

Discoloration

Total discolored kernel area increased with increasing storage MC, temperature, and storage duration, approaching 100% by the end of 16 weeks in samples stored at 21% MC and 40°C (Figure 2). Average discoloration levels also varied by cultivar and harvest year, with greater discoloration due to storage conditions in 2014 (Table 2). This was especially noticeable in samples stored at 21% MC at 27°C, where a unique pattern of discoloration was seen in both XL753 and CL XL745 in 2014, but not in 2015, when discoloration was relatively low at the same MC and temperature (Figure 3). Because of these differences, the data were subset into two overlapping halves for analysis; the 2014 data were analyzed for cultivar-specific responses to storage conditions between XL753 and CL XL745, and the CL XL745 data were analyzed for annual variability with respect to storage conditions in a single genetic background.

The total discolored kernel area data, when analyzed for normality of distribution, were found to be positively skewed, with most samples measured at very low discolored area values. The data were thus not appropriate for multiple linear regression due to a curved pattern in the plot of actual-by-predicted values, and in the residuals. Therefore, the data were transformed with the natural log function in an attempt to address this skew. This transformation was chosen for its simplicity, and because it normalized the appearance of the actual-by-predicted plot and the distribution of residuals in analysis. No other transformation, including the best Box-Cox transformation produced by the regression platform, fully normalized the data. In a longer-term storage study, use of nonlinear regression may be appropriate because of the natural asymptote of 100% kernel discoloration, but total discoloration was <100% in all samples, and trends appeared sufficiently linear over 16 weeks (Figure 2).

In the 2014 subset, cultivar was entered as a fixed effect in the multiple regression platform in interaction with all storage factors and their interactions, which were entered as continuous variables. Estimated regression coefficients presented in Table 3 were interpreted in terms of percent change in discoloration by the following standard formula for log-level regression:

$$\%\Delta(discolored\ kernel\ area\ \%) = 100 \times (e^{\beta} - 1)$$

Coefficients for MC were first multiplied by 0.01 for interpretation in terms of single percentage point (pp) increases.

In 2014, XL753 was significantly more susceptible to developing discoloration in storage than CL XL745; the average discoloration in XL753 was 19.2% and 10.9% for CL XL745 (Table 2). On average between cultivars, a 1 pp increase in storage MC increased discoloration by 16%, a 1°C increase in storage temperature increased discoloration by 7.3%, and a 1 week increase in storage duration increased discoloration by 4.9% (Table 3). Percentage-wise increases in discoloration due to storage MC and temperature were significantly greater in CL XL745 than in XL753 in 2014, but this resulted in lesser absolute increases due to lower baseline levels of discoloration in CL XL745.

In 2014, yellow was the predominant color at both 27°C and 40°C in rice stored at 21% MC (Figure 3), but at 40°C the milled rice appeared uniformly yellow with other colors only appearing at barely noticeable levels. At 27°C, however, a mottled pattern appeared, especially in cultivar XL753, with a combination of white, yellow, light pink, pink/red, black/brown, and red/brown kernels. This pattern was also apparent in CL XL745, but due to the low frequency of non-yellow discolored kernels in the samples from this cultivar stored at 21% MC and 27°C, these discolored kernels were not well represented in the 100-kernel sub-samples that were imaged for analysis. Because of this under-representation, a statistical evaluation of the effect of storage conditions on the incidence of these colors is not useful for describing observed patterns.

The first samples exhibiting these divergent color patterns were seen after 4-6 weeks of storage in both XL753 and CL XL745 in 2014. It was this pattern that prompted the use of image analysis software for quantifying discoloration. However, this pattern was not seen in the rice stored at 21% MC in the 27°C unit in 2015. The mechanism for the divergent color patterns is unknown, but these results corroborate findings from discolored rice samples obtained from on-farm bins. It was hypothesized upon seeing these results that the rice harvested in 2014 may have contained a greater proportion of thin kernels than in 2015. Thin kernels are known to have a greater individual kernel MC than thicker kernels, and as such may be more vulnerable to discoloration during storage (Siebenmorgen et al., 2006). This may be tested in future research by measuring kernel thickness in discolored samples from 2014 and 2015.

These results also raise the unanswered question of fungal involvement. Yellow discoloration occurred even in 12.5% MC rice stored at 40°C, consistent with the report of Bason et al. (1990) that yellowing was not prevented by MCs too low for fungal growth. However, it is interesting to note that studies that eliminated or otherwise ruled out fungi, such as those conducted by Bason et al. (1990) and Belefant-Miller et al. (2009), did not report any kind of variegated discoloration, as was found in this study at 21% MC and 27°C in 2014. The unique kernel colors actually suggest fungal infection, similar to what Schroeder (1965) demonstrated by inoculating sterile kernels with *Fusarium* to produce black and brown discoloration. Though the mechanisms of yellowing have still not been elucidated, this research lends support to the hypothesis that post-harvest discoloration in rice storage may be attributed to two different causes: one related to fungal growth and one related to biochemical changes initiated by storage MC, temperature, and duration.

In 2015, in addition to the lack of a unique color pattern at 27°C, discoloration was not significantly different between CL XL745 and XP760; each averaged approximately 3% total discolored area. In fact, CL XL745 in 2015 appeared more similar to XP760 in 2015, in terms of kernel discoloration, than to CL XL745 in 2014. In cultivar CL XL745, discoloration was significantly greater in 2014 than in 2015 (Table 2), and relative increases in discoloration with increasing storage duration were less than in 2014, but, as discussed previously with respect to cultivar differences in 2014, these were relative increases of lower baseline levels of discoloration. Therefore, absolute increases were less in 2015 than in 2014, as is apparent in Figure 2. In CL XL745 on average between years, a 1 pp increase in storage MC, 1°C increase in storage temperature, and 1 week increase in storage duration increased discoloration by 18%, 8.6%, and 10%, respectively. In 2014 with both XL753 and CL XL745, and with CL XL745 in both 2014 and 2015, the expected percent increases in discoloration due to interactions among storage conditions were only 0.5-1.5%, but the combined impact of these interactions was an overall increase in the slopes of the effects of storage MC, temperature, and duration when any other storage factor was increased.

Functionality

Average viscosity values generally differed significantly by cultivar (Table 2). Trends in viscosity due to storage conditions were consistent among cultivars and between harvest years, therefore interactions between cultivar-years and storage conditions were not analyzed. But viscosity trends diverged between 20-27°C and 40°C. This separation was well represented in the RVA profiles after 10 weeks of storage (Figure 4). After this storage duration, peak viscosities increased with increasing storage temperature from 20-27°C, but at 40°C peak viscosities were lesser on average than at 20-27°C and declined with increasing MC. Despite these reduced peak viscosities, trough and final viscosities were elevated with storage at 40°C, indicating reduced breakdown and high setback. Additionally, viscosity profiles at 40°C were positioned to the right of those at 20-27°C, showing an increase in pasting temperature.

Overall, peak viscosity (Figure 5), breakdown (Figure 6), and final viscosity (Figure 7) tended to increase initially during storage, then level off after about 8 weeks of storage at all storage MCs and at temperatures up to 27°C. These initial increases were greater at higher MCs and higher temperatures. Storage at all MCs and at temperatures of 40°C showed an initial increase followed by a sharp downturn in peak viscosity and breakdown after 4-6 weeks, indicating that such temperatures impacted starch structure and diminished water-holding capacity. Setback at 40°C sharply increased with increasing storage duration beginning after only 2 weeks (Figure 8). Peak time was significantly affected by storage conditions (data not shown), but the effects were too minute to have practical significance.

Because of the varying curvilinear effects of storage duration on viscosity parameters due to temperature, the data were subset by observations at 20-27°C and 40°C, and polynomial effects of storage duration up to quadratic (20-27°C) and cubic (40°C) levels were added to regression analyses. With storage at 20-27°C, peak viscosity (Figure 5) increased with increasing storage temperature (30 cP per 1°C) and duration (24.8 cP per week), but MC had no effect (Table 4). These effects tended to level off after 8 weeks. Trough viscosity was marginally affected by storage conditions, increasing slightly with increasing storage temperature and duration, and decreasing with increasing MC. Therefore breakdown at 20-27°C tended to increase with increasing storage temperature and duration, leveling off after 8-10 weeks (Figure

6). This trend in breakdown was reported by Patindol et al. (2005) with storage at 21°C, but was reversed in previous storage studies (Swamy et al., 1978; Sowbhagya and Bhattacharya, 2001; Kanlayakrit and Maweang, 2004).

Though at 20-27°C, final viscosity increased with increasing storage temperature and duration (Figure 7), these increases were less than the similar increases in peak viscosity. Therefore setback tended to decrease with increasing storage temperature, leveling off after 10 weeks (Figure 8). This decrease in setback was the reverse of previously reported aging effects (Swamy et al., 1978; Kanlayakrit and Maweang, 2004). The tendency of certain viscosity properties to increase initially, then level off after a certain storage duration elapsed is similar to what was described by Perdon et al. (1997), though that study reported viscosity peaking and either leveling off or declining after 3 months in storage, rather than approximately 2 months (8 weeks).

At 40°C (Table 5), peak viscosity increased with increasing duration, peaked after 4 weeks, then declined (Figure 5). Storage MC exerted a negative effect on peak viscosity at this temperature (Figure 4). Trough viscosity increased with increasing storage duration before leveling off after 6 weeks, but these effects were slight. Therefore breakdown increased in the first 2-4 weeks of storage, before peaking and declining thereafter (Figure 6). As with peak viscosity, declines in breakdown were greater at higher MCs. Final viscosity increased with increasing storage duration, and slightly with increasing MC, but only appeared to decrease after 10 weeks at MCs≥16% in 2014, and to a lesser extent in 2015 (Figure 7). Setback therefore increased with increasing storage duration after 2 weeks (Figure 8), primarily as a result of reductions in peak viscosity (Figure 5), and at the expense of kernel discoloration (Figure 2) at all MCs in 2014 and at MCs≥16% in 2015. Pasting temperature increased by nearly 1°C with each week of storage, beginning after 2 weeks at 40°C (Figure 9).

The trends of decreasing breakdown and increasing pasting temperature with storage at 40°C reproduced those reported by Patindol et al. (2005) with storage at 38°C. According to Patindol et al. (2005), the decline in breakdown and increase in pasting temperature at 38°C may be due to proteins stabilizing the swollen starch granules. With storage of rice at 40°C for 8-16 weeks, viscosity profiles demonstrate a reduced swelling capacity, high stability to shear stress, and extensive retrogradation as indicated by increasing setback and final viscosities.

E. Conclusions

This study only approximated conditions in storage or drying bins as the use of sealed jars created a hermetic environment. Despite the enclosed storage, this study reproduced findings from previous storage studies and replicated observed discoloration from on-farm rice bins; therefore, these approximations may be cautiously extrapolated to current storage or in-bin drying systems. The results demonstrate the importance of thorough drying, as well as proper temperature control. Though HRYs should not be negatively impacted, kernel discoloration can quickly develop in high-MC rice stored under ambient temperature conditions. Even fully dried rice was susceptible to significant discoloration when stored at 40°C. Hot, early-autumn temperatures typical of Arkansas rice harvest season, though they do not typically persist for 16 weeks, may endure long enough to degrade kernel quality in the moist, top layer of rice in a drying bin. Storage temperatures above 27°C should not be used for aging rice, due to the tendency for discoloration to develop and for peak viscosity to be negatively impacted after only 2-4 weeks of storage at 40°C. Aging rice for more than 8-12 weeks at 20-27°C does not appear to further enhance water-holding capacity.

The annual variability in the magnitude and pattern of kernel discoloration found in this study should guide future research towards a better understanding of post-harvest discoloration. Though prior research has attempted to rule out fungi as the primary cause of discoloration, it may be that a holistic mechanism of post-harvest discoloration should include fungal involvement as well as changes within the kernel due to MC, temperature, and duration. If the coincident effects of biological and biochemical factors on discoloration can be conclusively demonstrated, one practical solution can address both issues: proper drying and storage at or below 27°C should be inhospitable to fungi and prevent yellowing induced by storage conditions.

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G. Tables and Figures

Table 1. Overview of experimental design.

Cultivar – Harvest Year	Moisture Content (%)	Temperature (°C)	Duration (weeks)
XL753 – 2014	12.5	20	2
CL XL745 – 2014	16	27	4
CL XL745 – 2015	19	40	6
XP760 – 2015	21		8
			10
			12
			16

Table 2. Least square (LS) means for head rice yield, kernel discoloration, and viscosity properties by cultivar and year. Means for viscosity parameters were determined from the 20-27°C subset. Significant differences between means were tested by Tukey's HSD.

Parameter	Cultivar	Year	LS Mean		Std Error	95% CI
Head rice yield (%)	CL XL745	2014	52.80%	C	0.22%	52.4%, 53.3%
	CL XL745	2015	56.80%	A	0.22%	56.4%, 57.3%
	XP760	2015	54.60%	B	0.22%	54.2%, 55.0%
ln[Discolored area (%)]	XL753	2014	-1.65	A	0.046	-1.75, -1.56
	CL XL745	2014	-2.22	B	0.046	-2.31, -2.13
	CL XL745	2015	-3.44	C	0.062	-3.56, -3.31
	XP760	2015	-3.46	C	0.062	-3.58, -3.34
Peak viscosity (cP)	XL753	2014	3493	A	17.2	3460, 3527
	CL XL745	2014	3053	C	17.3	3019, 3087
	CL XL745	2015	3146	B	17.3	3112, 3180
	XP760	2015	3083	C	17.1	3049, 3117
Trough viscosity (cP)	XL753	2014	1665	A	9.1	1647, 1683
	CL XL745	2014	1555	B	9.1	1537, 1573
	CL XL745	2015	1472	C	9.2	1454, 1490
	XP760	2015	1444	C	9.1	1426, 1462
Breakdown (cP)	XL753	2014	1828	A	13.1	1803, 1854
	CL XL745	2014	1498	C	13.1	1472, 1524
	CL XL745	2015	1674	B	13.2	1648, 1700
	XP760	2015	1639	B	13	1613, 1665
Final viscosity (cP)	XL753	2014	3168	A	10.0	3148, 3188
	CL XL745	2014	3129	B	10.0	3109, 3149
	CL XL745	2015	3129	B	10.1	3109, 3149
	XP760	2015	2960	C	10.0	2940, 2980

Table 2 (Cont.)

Parameter	Cultivar	Year	LS Mean		Std Error	95% CI
Setback (cP)	XL753	2014	-325.5	D	12.4	-350, -301
	CL XL745	2014	76.3	A	12.5	52, 101
	CL XL745	2015	-17.3	B	12.5	-42, 7
	XP760	2015	-123	C	12.4	-147, -99
Pasting temperature (°C)	XL753	2014	81.6	A	0.048	81.5, 81.7
	CL XL745	2014	79.9	B	0.048	79.8, 80
	CL XL745	2015	78.7	C	0.048	78.6, 78.7
	XP760	2015	78.6	C	0.048	78.5, 78.7

Table 3. Multiple regression model parameter estimates, standard errors, P-values, and 95% confidence intervals for the natural log of discolored kernel area (%) in 2014 (cultivars XL753 and CL XL745) and for cultivar CL XL745 (years 2014 and 2015). Continuous factors are centered by mean. Adjusted R^2 values are indicated beneath Parameter labels.

Parameter	**Term**	**Estimate**	**Std Error**	**Prob<|t|**	**95% CI**
ln[Discolored area (%)]	Intercept	-6.98	0.180	<.0001	-7.3, -6.6
2014	745	-0.28	0.028	<.0001	-0.34, -0.23
86%	753	0.28	0.028	<.0001	0.23, 0.34
	745*T	0.013	0.003	0.0002	0.0065, 0.020
	745*MC	3.2	0.791	<.0001	1.6, 4.7
	745*D	0.0050	0.006	0.4308	-0.0075, 0.017
	745*MC*D	0.44	0.172	0.0111	0.10, 0.78
	T	0.071	0.003	<.0001	0.064, 0.078
	MC	14.8	0.799	<.0001	13.2, 16.3
	T*MC	0.15	0.093	0.1102	-0.034, 0.33
	D	0.048	0.006	<.0001	0.036, 0.061
	T*D	0.0041	0.001	<.0001	0.0026, 0.0056
	MC*D	0.51	0.175	0.0042	0.16, 0.86
	T*MC*D	-0.074	0.019	0.0002	-0.11, -0.036
ln[Discolored area (%)]	Intercept	-8.8	0.27	<.0001	-9.3, -8.3
CL XL745	2014	0.55	0.042	<.0001	0.47, 0.63
85%	2014*MC	0.67	1.3	0.5945	-1.8, 3.1
	2014*D	-0.050	0.0087	<.0001	-0.067, -0.033
	2014*MC*D	-0.67	0.27	0.0132	-1.2, -0.14
	T	0.083	0.0050	<.0001	0.073, 0.092
	MC	16.2	1.3	<.0001	13.7, 18.7
	T*MC	0.54	0.15	0.0004	0.24, 0.84
	D	0.099	0.0087	<.0001	0.082, 0.12
	T*D	0.0059	0.0010	<.0001	0.0039, 0.0079
	MC*D	1.4	0.2666	<.0001	0.91, 2.0

***** 753-14: XL753 in 2014; 745-14: CL XL745 in 2014; 745-15: CLXL745 in 2015; 760-15: XP760 in 2015; MC: moisture content (%); T: temperature (°C); D: storage duration (weeks)

Table 4. Multiple regression model parameter estimates, standard errors, P-values, and 95% confidence intervals for viscosity responses with storage at 20-27°C. Nominal factors are expanded to all levels and continuous factors are centered by mean. Adjusted R^2 values are indicated beneath Parameter labels.

Parameter	Term	Estimate	Std Error	Prob<|t|	95% CI
Peak viscosity (cP)	Intercept	2310	53.3	<.0001	2204.5, 2414.7
80%	753-14	299.3	13.2	<.0001	273.3, 325.3
	745-14	-140.3	13.3	<.0001	-166.4, -114.1
	745-15	-47.0	13.3	0.0005	-73.2, -20.9
	760-15	-111.9	13.2	<.0001	-137.9, -85.9
	T	30.0	2.2	<.0001	25.7, 34.3
	D	24.8	1.6	<.0001	21.7, 27.9
	T*D	2.2	0.43	<.0001	1.4, 3.1
	D^2	-2.2	0.31	<.0001	-2.8, -1.6
Trough viscosity	Intercept	1429	34.3	<.0001	1361.8, 1496.9
67%	753-14	131.1	7.0	<.0001	117.4, 144.9
	745-14	21.2	7.0	0.0028	7.4, 35
	745-15	-62.4	7.0	<.0001	-76.2, -48.5
	760-15	-90	7.0	<.0001	-103.7, -76.2
	T	5.0	1.15	<.0001	2.7, 7.3
	MC	-237.8	115.4	0.0403	-465, -10.6
	D	3.24	0.8	<.0001	1.7, 4.8
	T*D	0.69	0.23	0.0028	0.2, 1.1
Breakdown (cP)	Intercept	917	40.6	<.0001	837, 997.1
80%	753-14	168.5	10.1	<.0001	148.7, 188.3
	745-14	-162	10.1	<.0001	-181.9, -142.1
	745-15	14.8	10.1	0.144	-5.1, 34.8
	760-15	-21.3	10.1	0.035	-41.1, -1.5
	T	25	1.7	<.0001	21.8, 28.3
	D	21.3	1.2	<.0001	18.9, 23.6
	T*D	1.6	0.33	<.0001	0.9, 2.2
	D^2	-2.0	0.24	<.0001	-2.5, -1.5
Final viscosity (cP)	Intercept	2642	37.9	<.0001	2567.8, 2717.2
74%	753-14	71.5	7.7	<.0001	56.4, 86.6
	745-14	32.7	7.7	<.0001	17.5, 47.9
	745-15	32.4	7.7	<.0001	17.2, 47.6
	760-15	-136.6	7.7	<.0001	-151.7, -121.5
	T	14.3	1.3	<.0001	11.8, 16.9
	MC	94.2	127.2	0.4599	-156.4, 344.7
	D	13.8	0.91	<.0001	12, 15.6
	T*D	1.6	0.25	<.0001	1.1, 2.1
	MC*D	58.3	25.3	0.0221	8.4, 108.2
	D^2	-0.88	0.18	<.0001	-1.2, -0.52
Setback (cP)	Intercept	289	47.2	<.0001	196.6, 382.3

Table 4 (Cont.)

Parameter	Term	Estimate	Std Error	Prob<|t|	95% CI
79%	753-14	-228.1	9.5	<.0001	-246.9, -209.3
	745-14	173.7	9.6	<.0001	154.8, 192.6
	745-15	80.1	9.6	<.0001	61.2, 99
	760-15	-25.6	9.6	0.0078	-44.5, -6.8
	T	-15.7	1.6	<.0001	-18.8, -12.6
	MC	352.6	158.1	0.0266	41.2, 663.9
	D	-10.9	1.1	<.0001	-13.2, -8.7
	T*D	-0.71	0.31	0.0253	-1.3, -0.1
	MC*D	101.7	31.5	0.0014	39.7, 163.7
	D^2	1.3	0.23	<.0001	0.9, 1.8

***** 753-14: XL753 in 2014; 745-14: CL XL745 in 2014; 745-15: CLXL745 in 2015; 760-15: XP760 in 2015; MC: moisture content (%); T: temperature (°C); D: storage duration (weeks)

Table 5. Multiple regression model parameter estimates, standard errors, P-values, and 95% confidence intervals for viscosity responses with storage at 40°C. Nominal factors are expanded to all levels and continuous factors are centered by mean. Adjusted R^2 values are indicated beneath Parameter labels.

Parameter	Term	Estimate	Std Error	Prob<|t|	95% CI
Peak viscosity (cP)	Intercept	4427	115.2	<.0001	4198.9, 4655.2
79%	753-14	370.8	33.0	<.0001	305.5, 436.2
	745-14	-208.2	33.0	<.0001	-273.6, -142.8
	745-15	-87.5	33.0	0.0091	-152.9, -22.2
	760-15	-75.1	33.0	0.0248	-140.5, -9.7
	MC	-2414.0	488.5	<.0001	-3381.1, -1446.8
	D	-120.5	9.7	<.0001	-139.8, -101.3
	D^2	-8.7	0.88	<.0001	-10.5, -7
	D^3	1.5	0.19	<.0001	1.2, 1.9
Trough viscosity (cP)	Intercept	1730	44.1	<.0001	1642.4, 1816.9
76%	753-14	176.4	12.5	<.0001	151.7, 201.1
	745-14	11.8	12.5	0.3463	-12.9, 36.5
	745-15	-69.6	12.5	<.0001	-94.3, -44.9
	760-15	-118.6	12.5	<.0001	-143.3, -93.9
	MC	-188.0	188.9	0.3217	-562.2, 186.1
	D	5.8	3.7	0.1147	-1.4, 13.1
	MC*D	-99.3	35.9	0.0065	-170.4, -28.3
	D^2	-2.6	0.33	<.0001	-3.3, -1.98
	D^3	0.21	0.070	0.0034	0.071, 0.35
Breakdown (cP)	Intercept	2678	111.3	<.0001	2457.5, 2898.2
79%	753-14	192.6	31.9	<.0001	129.5, 255.8
	745-14	-217.9	31.9	<.0001	-281.1, -154.8
	745-15	-17.8	31.9	0.5783	-80.9, 45.4
	760-15	43.1	31.9	0.1793	-20.1, 106.2
	MC	-2112.0	471.8	<.0001	-3046.2, -1177.8
	D	-126.4	9.4	<.0001	-145, -107.8
	D^2	-6.1	0.85	<.0001	-7.8, -4.4
	D^3	1.3	0.18	<.0001	0.96, 1.7
Final viscosity (cP)	Intercept	3344	68.0	<.0001	3209.4, 3478.5
83%	753-14	199.4	19.5	<.0001	160.9, 238
	745-14	-40.0	19.5	0.0423	-78.5, -1.4
	745-15	-4.0	19.5	0.8368	-42.6, 34.6
	760-15	-155.5	19.5	<.0001	-194.02, -116.9
	MC	207.7	288.2	0.4726	-362.9, 778.2
	D	33.5	5.7	<.0001	22.1, 44.9
	D^2	-6.1	0.52	<.0001	-7.1, -5.1
	D^3	0.31	0.11	0.0059	0.09, 0.53
Setback (cP)	Intercept	-1083	116.0	<.0001	-1312.7, -853.5
86%	753-14	-171.4	33.2	<.0001	-237.2, -105.6

Table 5 (Cont.)

Parameter	Term	Estimate	Std Error	Prob<|t|	95% CI
	745-14	168.2	33.2	<.0001	102.4, 234
	745-15	83.5	33.2	0.0133	17.7, 149.3
	760-15	-80.4	33.2	0.0171	-146.2, -14.6
	MC	2621.6	491.7	<.0001	1648, 3595.2
	D	154.0	9.8	<.0001	134.6, 173.4
	D^2	2.7	0.88	0.003	0.92, 4.4
	D^3	-1.2	0.19	<.0001	-1.6, -0.85
Pasting temperature (°C)	Intercept	75.7	0.70	<.0001	74.3, 77.1
85%	753-14	0.72	0.20	0.0005	0.32, 1.1
	745-14	0.84	0.20	<.0001	0.44, 1.24
	745-15	-0.48	0.20	0.0189	-0.87, -0.08002
	760-15	-1.1	0.20	<.0001	-1.5, -0.68
	MC	14.9	3.0	<.0001	9, 20.7
	D	0.77	0.059	<.0001	0.65, 0.89
	D^2	-0.0048	0.0053	0.3739	-0.015, 0.0058
	D^3	-0.0038	0.0011	0.0010	-0.0061, -0.0016

***** 753-14: XL753 in 2014; 745-14: CL XL745 in 2014; 745-15: CLXL745 in 2015; 760-15: XP760 in 2015; MC: moisture content (%); T: temperature (°C); D: storage duration (weeks)

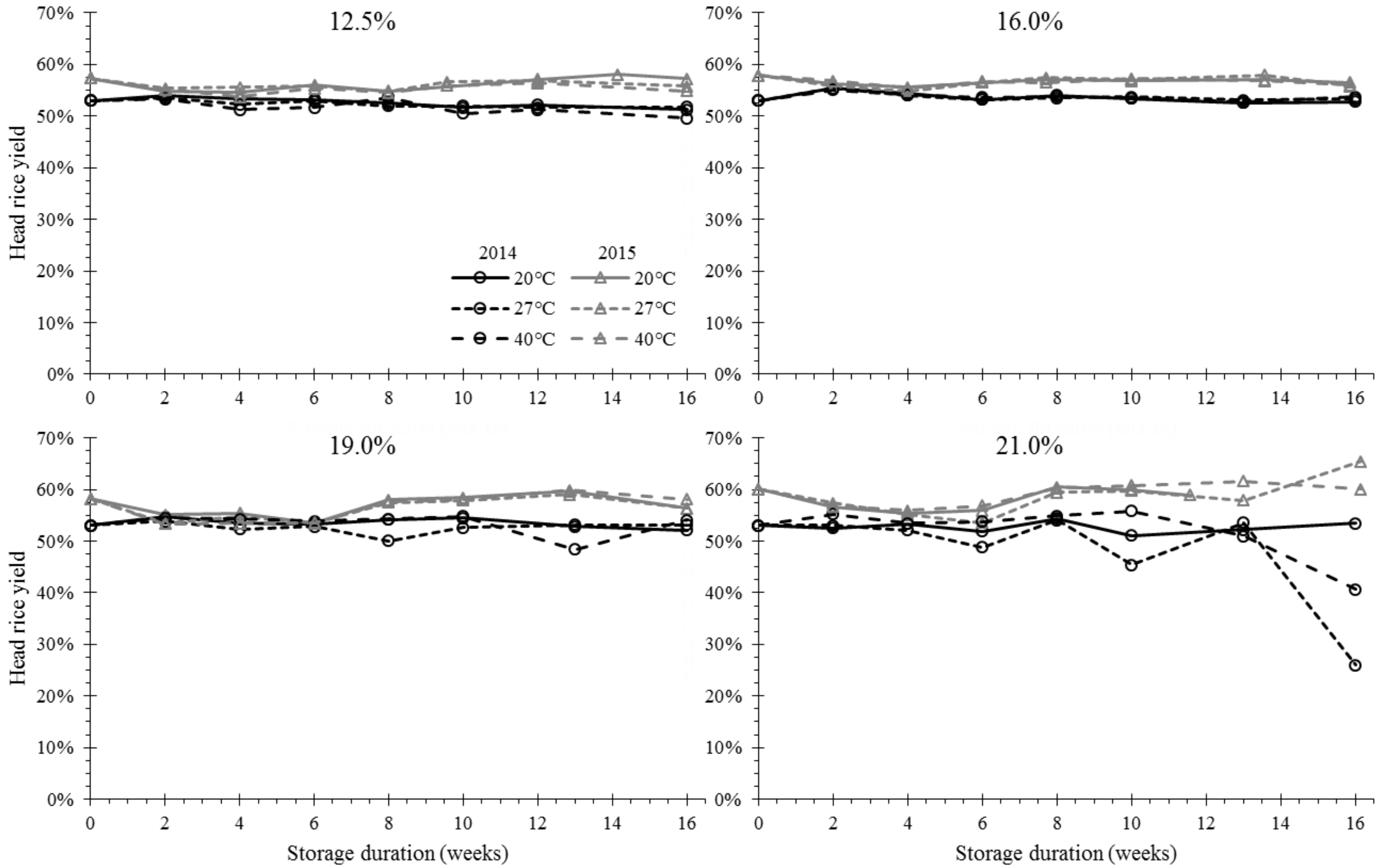

Figure 1. Effects of the indicated moisture contents and temperatures on head rice yield (%) in cultivar CL XL745 during storage in 2014 (○) and 2015 (Δ).

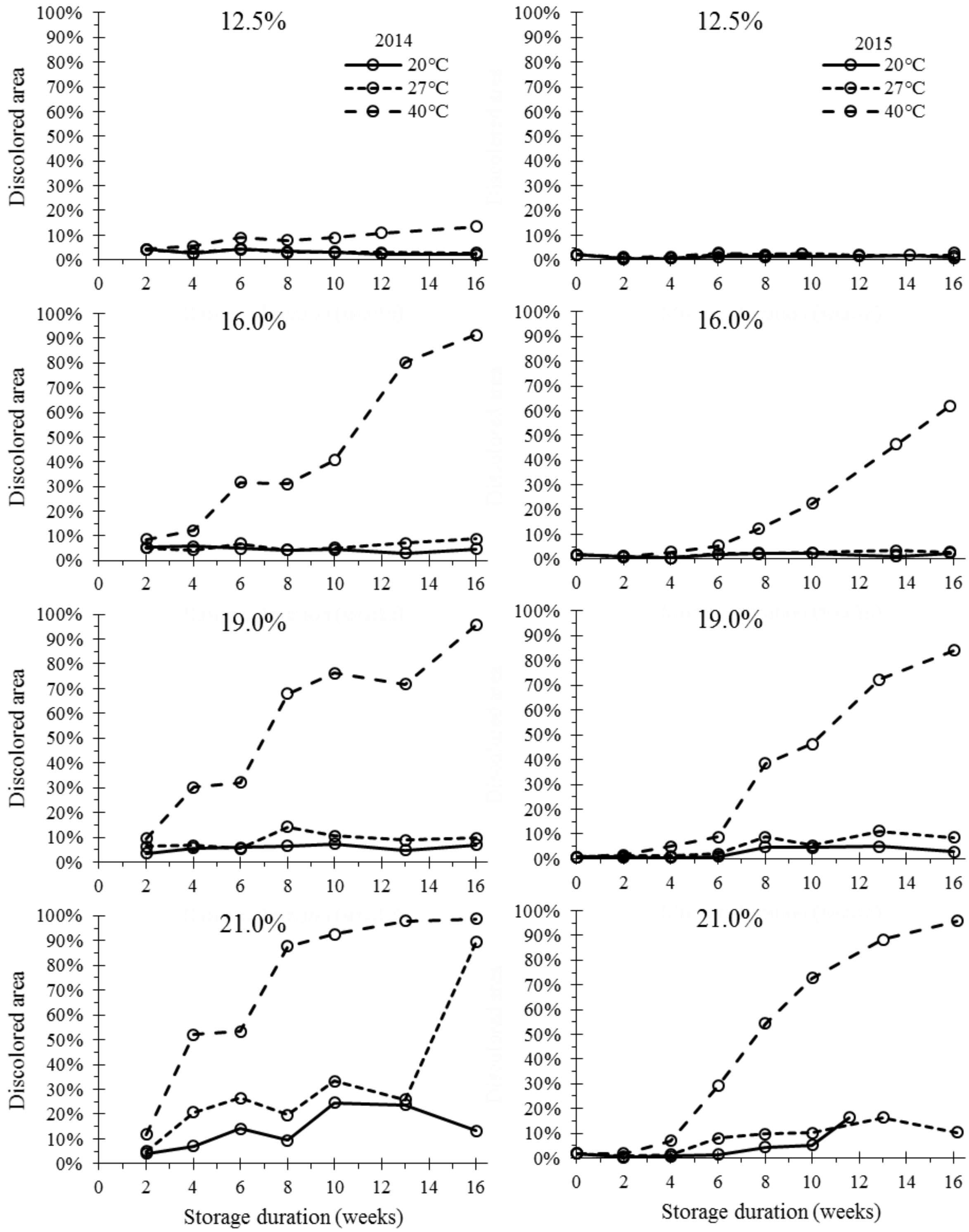

Figure 2. Effects of the indicated moisture contents and temperatures on total discolored kernel area in cultivar CL XL745 during storage in 2014 (left) and 2015 (right).

Figure 3. Extent and make-up of discolored head rice kernel area after 10 weeks of storage for specified cultivars and harvest years at indicated moisture contents and temperatures.

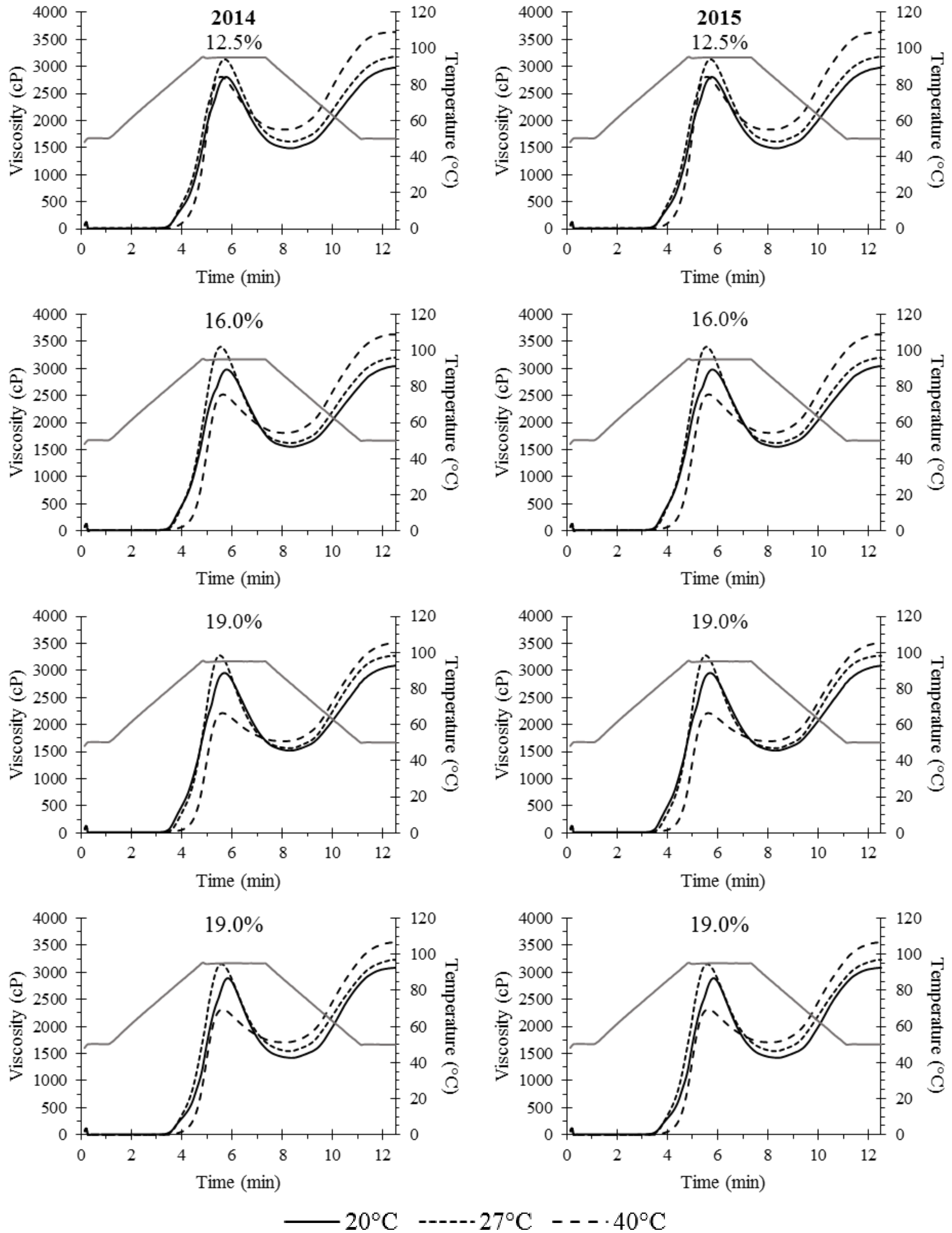

Figure 4. Rapid Visco Analyser profiles for cultivar CL XL745 stored for 10 weeks in 2014 (left) and 2015 (right) at indicated moisture contents and temperatures.

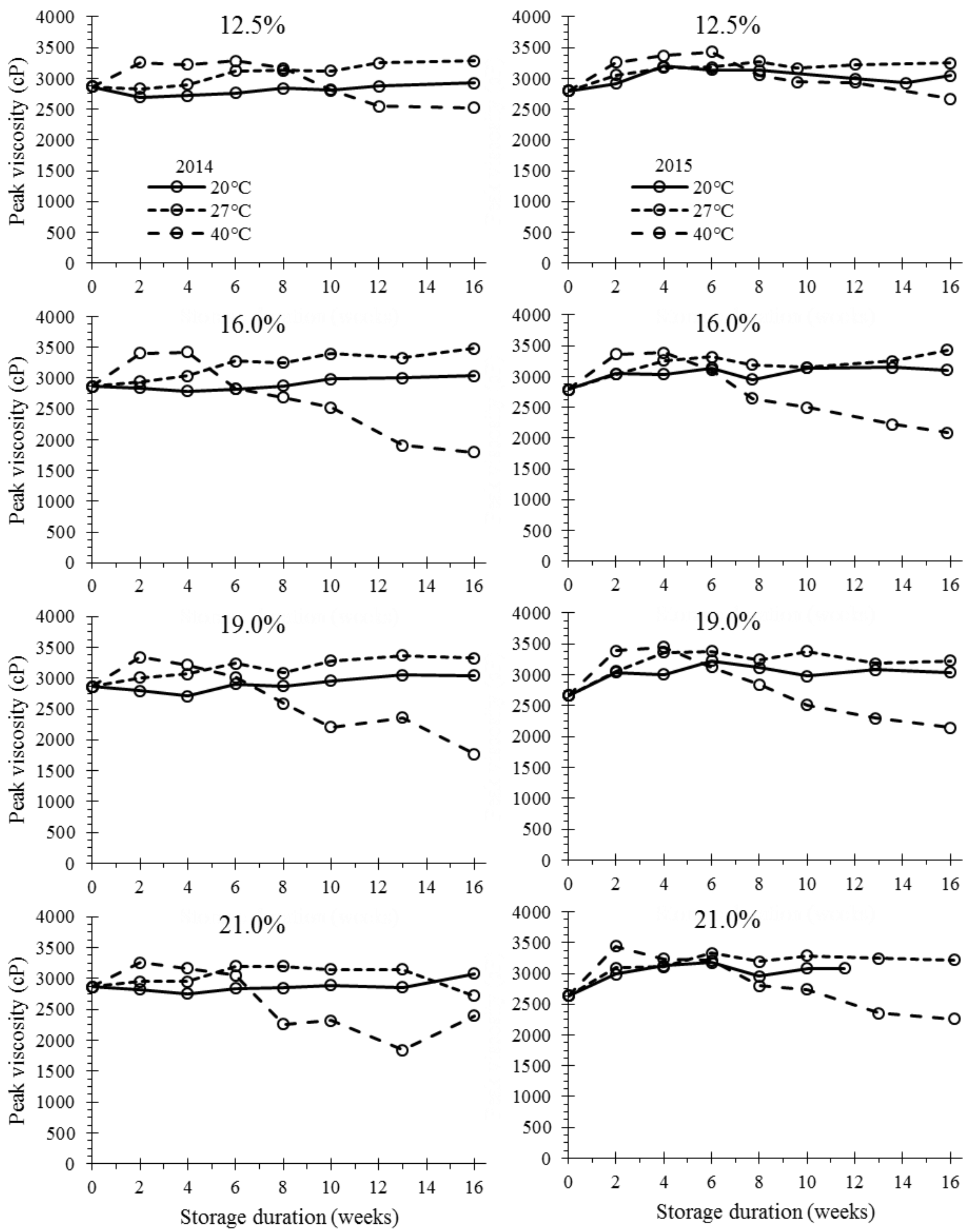

Figure 5. Effects of the indicated moisture contents and temperatures on peak viscosity (centipoise) of cultivar CL XL745 during storage in 2014 (left) and 2015 (right).

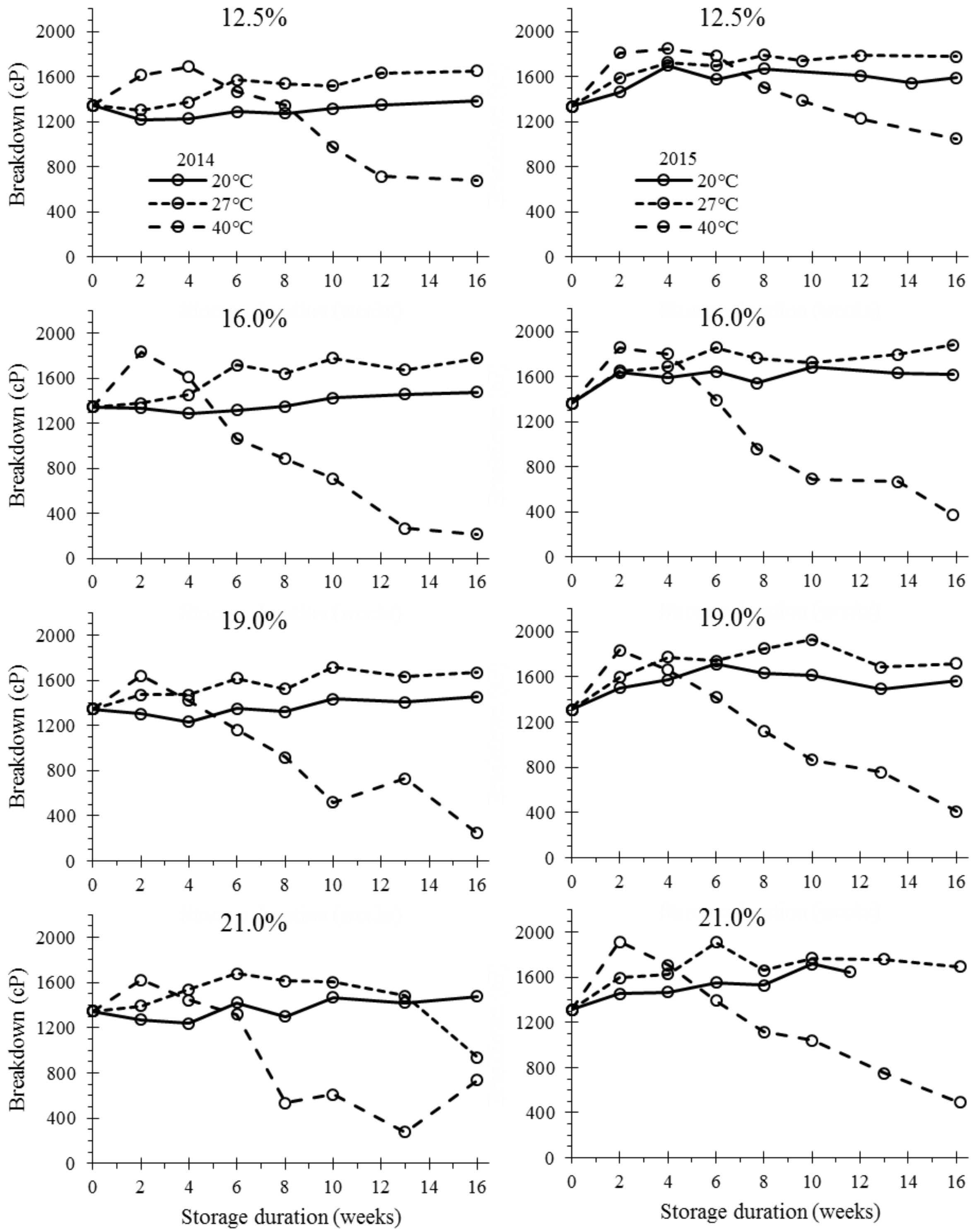

Figure 6. Effects of the indicated moisture contents and temperatures on breakdown (peak-trough viscosity; centipoise) of cultivar CL XL745 during storage in 2014 (left) and 2015 (right).

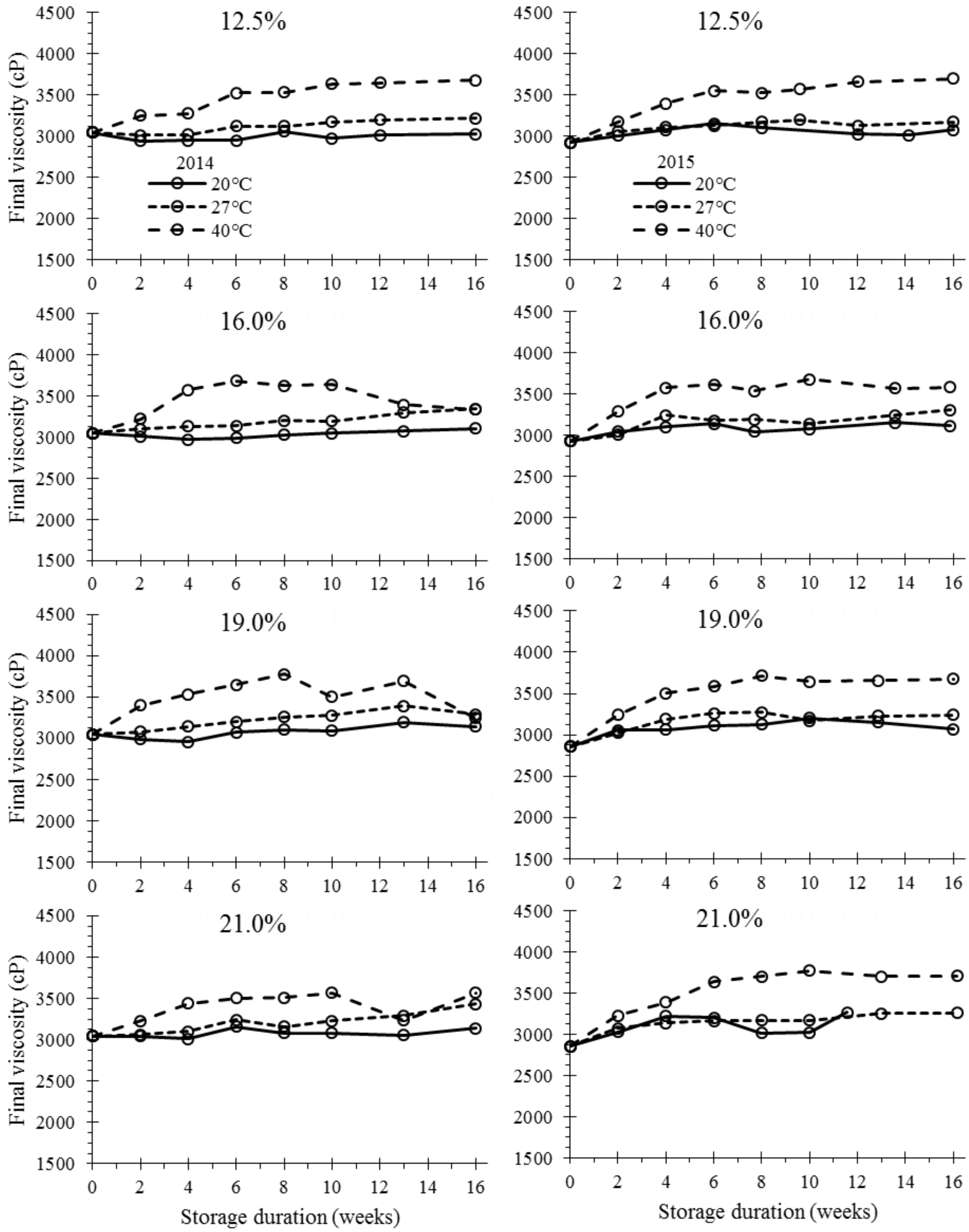

Figure 7. Effects of the indicated moisture contents and temperatures on final viscosity (centipoise) of cultivar CL XL745 during storage in 2014 (left) and 2015 (right).

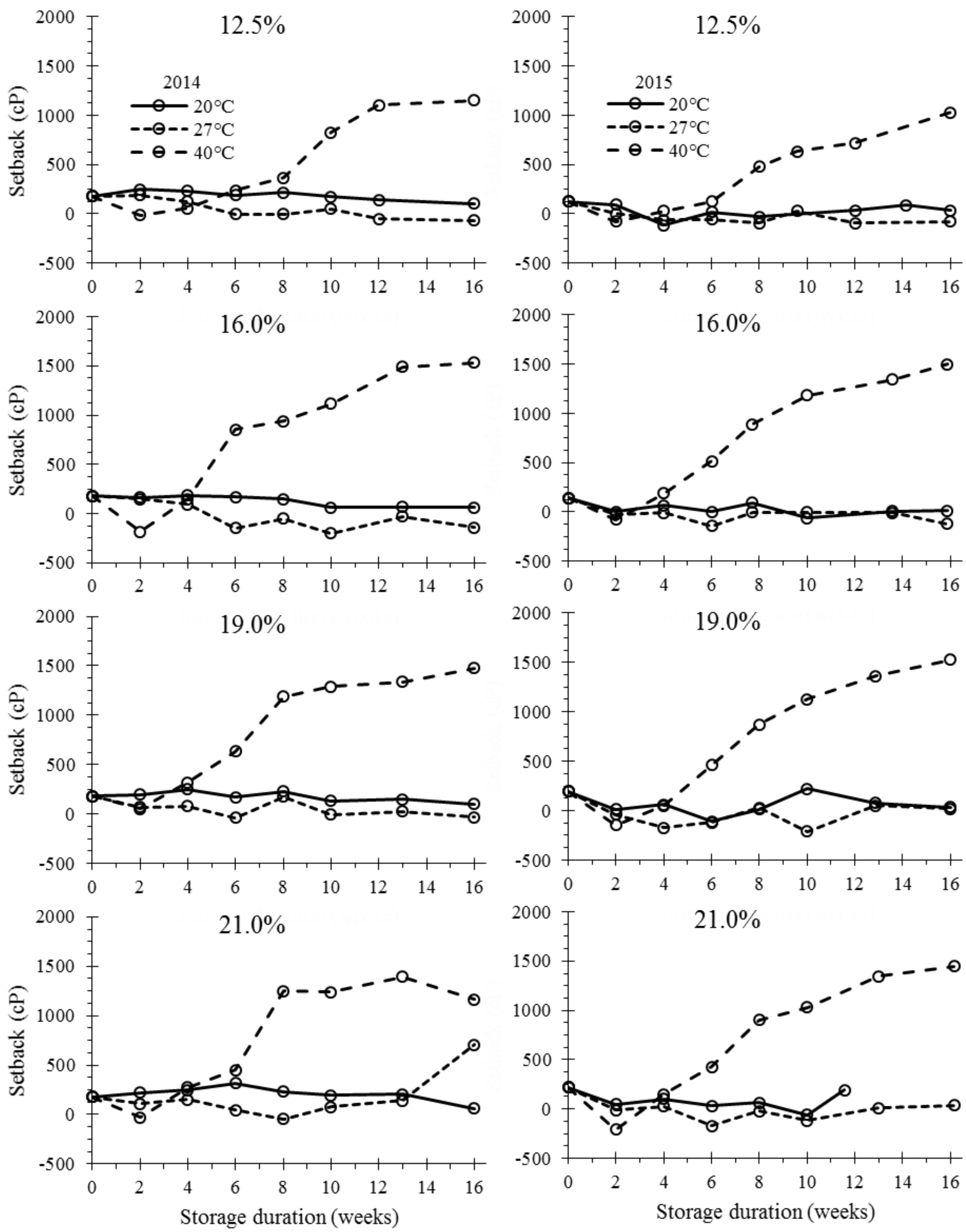

Figure 8. Effects of the indicated moisture contents and temperatures on setback (final-peak viscosity; centipoise) of cultivar CL XL745 during storage in 2014 (left) and 2015 (right).

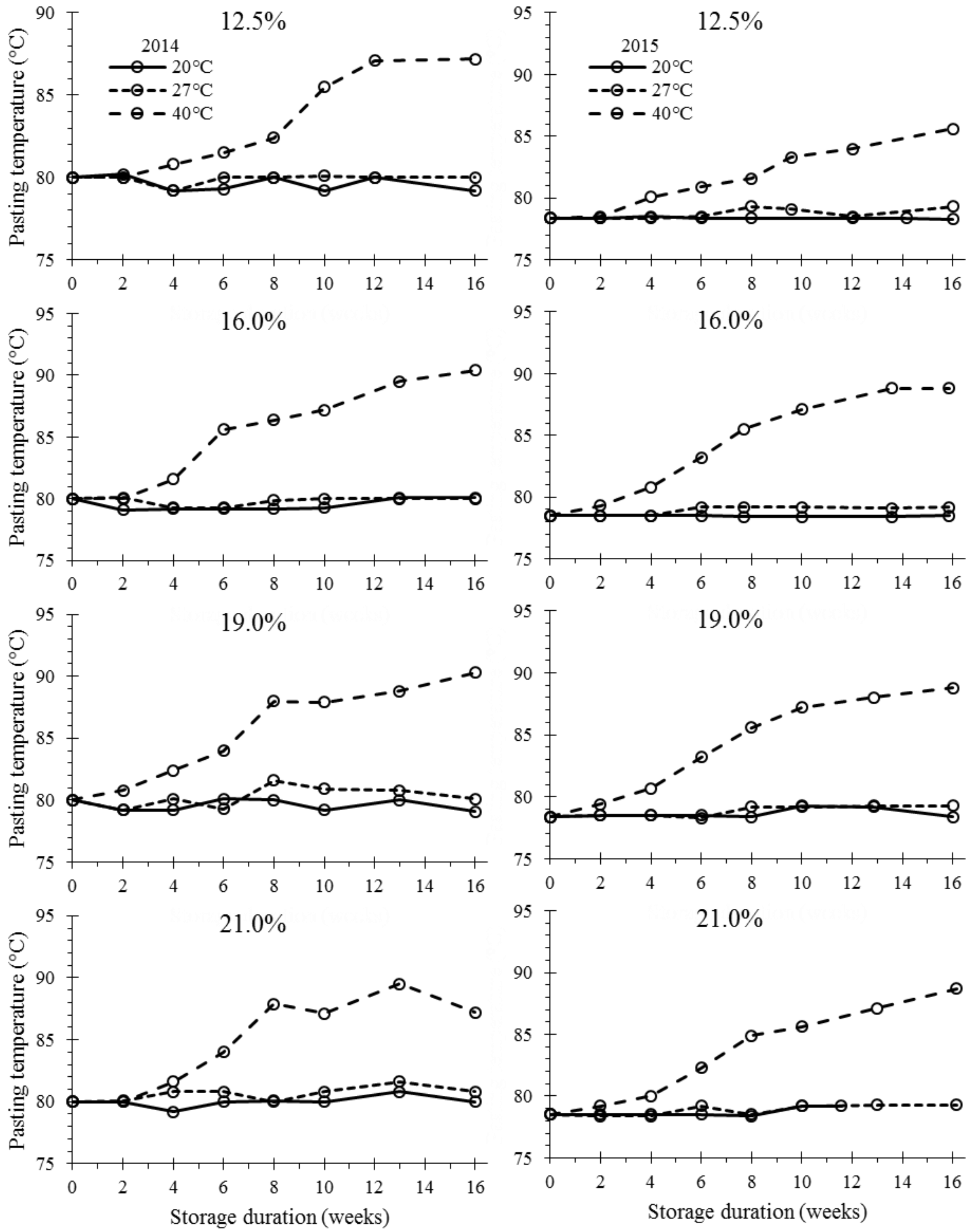

Figure 9. Effects of the indicated moisture contents and temperatures on pasting temperature (°C) of cultivar CL XL745 during storage in 2014 (left) and 2015 (right).

III. Potential of Grain Cooling to Preserve Quality of High-Moisture Content Rough Rice during Short-Term Storage

A. Abstract

High-moisture content (MC) rough rice cannot be stored for long durations using conventional systems without suffering degradation due to mold growth and coincident discoloration. Delayed drying, in concert with grain cooling, has been proposed as a technique for preserving the quality of high-MC rice before drying or parboiling. Cooling systems for grain storage are commercially available, but not currently employed in the Mid-South United States rice industry. This study evaluated whether long-grain rough rice stored at 12.5%, 16%, 19%, and 21% MC for up to 16 weeks retains milling yields, head rice kernel color, and functionality characteristics during cooled and ambient storage (10°C, 15°C, and 20°C). Head rice yield (HRY) was maintained at all MC and temperature combinations throughout the entire storage duration. However, the storage conditions necessary for maintaining kernel color depended on cultivar and harvest year as well as storage MC. Cool storage temperatures also retarded expected increases in peak viscosity, and final viscosity to a lesser extent. Trough viscosity was not affected, therefore minimum breakdown and maximum setback were achieved after storage for 16 weeks at 21% MC and 10°C. Aging effects leveled off or began to decrease after 8-12 weeks of storage, regardless of cultivar, MC, or temperature. The results of this study revealed cultivar and annual variability in discoloration that should be understood before recommending cooling of all long-grain cultivars at elevated harvest MCs. Additionally, the potential effects of grain cooling on end-use operations, such as parboiling, should be considered.

B. Introduction

Safe storage of rough rice typically depends on drying to reduce moisture content (MC), and thus water activity, to sufficiently low levels to minimize respiration, fungal growth, and kernel discoloration. Some fungi, when stressed, can produce mycotoxins, poisonous compounds that can cause illness and death in people and animals when ingested in sufficient dosages. Discoloration leads to downgrading or rejection of rice at the point of sale. These two issues may be related, though there is considerable debate in the literature about fungal responsibility for kernel discoloration (Schroeder, 1963, 1965; Bason et al., 1990; Belefant-Miller, 2009).

Nevertheless, there are several possible advantages to temporarily storing high-MC rough rice. For optimal milling yields, long-grain rice in Arkansas is harvested at 19-21% MC[2], then dried to 12-13% before further processing. Commercial dryers experience pressure during harvest to dry every customer's rice as quickly as possible. Delays can lead to quality degradation and subsequent profit losses. Some fresh rice is immediately parboiled when it arrives at processing facilities, wherein the rice is soaked to at least 30% MC, steamed, and then dried. However, large processors parboil rice year-round, and when the supply of fresh rice is depleted after harvest, dried rice from storage becomes the primary feedstock. Therefore most of the rice that is parboiled throughout the year is dried twice: before and after parboiling.

A safe, temporary storage option for high-MC rice would reduce the pressure on commercial dryers to dry all fresh rice within a limited timeframe without quality losses, and could eliminate pre-parboil drying steps for at least a significant fraction of the annual amount of rice parboiled, potentially saving energy. Other purported benefits of grain cooling include reduction of dry matter loss, prevention of insect infestation, mold growth, and discoloration, a

[2] All moisture contents are given on a wet-basis.

small reduction in grain MC thereby reducing drying costs, and preservation of head rice yield (HRY) (Kolb; Kolb and Braunbeck). According to Brunner (1986), cooling was used in Europe in the 1960s to preserve high-MC grain in the interim between harvest and drying, but this use has mostly been replaced by cooling grain harvested at low MCs to prevent insect infestations; fumigation costs can thus be reduced by cooling (Rulon et al., 1999; Lazzari et al., 2006). The potential for cooling rough rice at harvest MCs to prevent milling yield reductions or postharvest kernel discoloration has not been fully explored.

Most studies that have induced kernel discoloration in rice, whether in rough, brown, or milled form, used very high temperatures in the range of 52-70°C (Bason et al., 1990; Dillahunty et al., 2001; Belefant-Miller et al., 2005; Belefant-Miller, 2009; Ambardekar and Siebenmorgen, 2012; Bryant et al., 2013; Belefant-Miller and Grunden, 2014). Fungal growth has been hypothesized as a cause of discoloration because it generally appears concurrent with discoloration. Schroeder (1965) induced discoloration by inoculating sterile kernels with particular species of fungi, but other research has found no evidence that fungi are directly implicated (Bason et al., 1990; Belefant-Miller et al., 2005). Regardless of whether fungi are responsible to any degree for discoloration, reducing fungal growth would be very beneficial for farmers, processors, and ultimately, consumers.

Physicochemical properties of rice are known to change with storage duration, and these may have positive effects on end-use quality depending on desired final product characteristics. Cooking and sensory qualities are significantly affected; storage increases the hardness and fluffiness of cooked rice and decreases stickiness (Villareal et al., 1976; Bolling et al., 1978; Chrastil, 1990 a). Flavor perceptions are also impacted by storage conditions (Meullenet et al., 2000). However, most of these studies investigated effects in multi-year storage scenarios, so the results may be of limited application in relatively short-term, cooled-storage arrangements. But, because storage effects on physicochemical properties have significant consequences for consumer quality, the effect of cold storage on these properties must be considered.

Viscosity analysis provides a useful predictor of rice cooking quality. Peak viscosity, for example, provides an estimate of rice's water-holding or swelling capacity. Long-term storage of 12-14% MC rice at room temperature caused a gradual increase in peak viscosity over time, followed by a decrease after 20 months in the study by Sowbghaya and Bhattacharya (2001). However, Perdon et al. (1997) noted a leveling off of peak viscosity after 3 months in rice stored at 12.9% and 13.6% MC for 6 months. Kanlayakrit and Maweang (2004) found that breakdown, which is the difference between peak and trough viscosity, decreased over time in storage at 20°C, 30°C, and 40°C, indicating that the starch becomes more ordered and stable to shear stress. The same study also found setback (final-peak viscosity), pasting temperature, and duration required to reach peak temperature (peak time) increased during storage, further suggesting that the stability of the starch increases, even though the water-holding capacity, represented by peak viscosity, eventually started to stabilize or decrease. Cold storage (1-3°C) has been shown to slow these changes in viscosity properties, while high-temperature storage up to 38°C and storage at MCs up to 14% accelerate these processes (Swamy et al., 1978; Kumar and Ali, 1991; Pearce and Marks, 2001).

The causes of aging effects are not fully understood, but they are generally only apparent in rice flour, rather than isolated starch, indicating that other components, such as proteins and lipids, are responsible (Teo et al., 2000; Zhou et al., 2002, 2003). Enzyme activity changes significantly during storage, and previous studies suggested that decreased amylase activity gave aged rice its superior cooking quality (Chrastil, 1990 b; Dhaliwal et al., 1991). This hypothesis has been rejected by Desikachar and Subramanyan (1960) because of the finding that amylases are quickly deactivated during cooking and have no effect on the final product. Physical changes were proposed by Desikachar and Subramanyan (1960) as being the true cause of enhanced cooking quality due to aging. These physical changes may include starch fine structure reconfigurations during storage at 38°C (and to a lesser extent at 21°C) described by Pattindol et al. (2005), including a decreased amylose to amylopectin ratio, shortened average amylopectin chain lengths, and a shift in chain length distribution to shorter lengths.

This study was undertaken to establish the upper limits of rough rice MC, temperature, and duration in a cool-storage environment that could be used to preserve HRY and milled rice color after harvest. No storage studies were found that included rough rice at high-to-optimum harvest MCs stored under cooling temperatures feasible for extended durations with large grain masses; studies that included storage harvest MCs either used temperatures of 1-4°C, or moderate-to-high temperatures of 20-70°C in order to induce aging effects and/or discoloration. Thus, this study aimed to establish the kinetics of possible HRY reductions and discoloration development in rice cultivars harvested in different years when stored under low-temperature, high-MC conditions. It was expected that physicochemical properties would be altered by cool storage at high MCs; thus, functional properties were measured throughout the storage duration to determine whether the changes could present a practically significant disadvantage to short-term cooling if particular end-use quality is desired.

C. Materials and Methods

This study was conducted with three long-grain, hybrid rice cultivars harvested in AR in two years, 2014 and 2015. In 2014, XL753 was produced at the University of Arkansas Northeast Rice Research and Extension Center near Keiser, AR, and CL XL745 was obtained from Running Lake Farms in Pocahontas, AR. Both cultivars were harvested at approximately 22% MC; in 2015, XP760 and CL XL745, both grown in Pocahontas, were harvested at 22% and 21% MC, respectively. The rough rice was cleaned using a dockage tester (Model XT4, Carter-Day, Minneapolis, MN) within two days of harvest. After cleaning, the rice was temporarily stored in a walk-in cooler at 4°C before it was spread on tarps and conditioned at room temperature with periodic mixing to MCs of 12.5%, 16%, 19%, and 21% as measured by a moisture tester (AM 5200, Perten Instruments, Hägersten, Sweden). In some cases, ambient air conditions were not sufficient to attain the 12.5% MC level; for these cases, the drying was finished in a chamber with air conditions maintained at 27°C and 60% relative humidity by a temperature- and humidity-control unit (AA5582, Parameter Generation and Control, Inc., Black Mountain, NC). The initial MC of each conditioned portion was verified by drying two, 15-g samples in a 130°C oven (1370FM, Sheldon Mfg. Inc., Cornelus, OR) for 24 h (Jindal and Siebenmorgen, 1987).

After conditioning, one sample from each MC sub-set of each cultivar was immediately dried to 12.5% and set aside for analysis as the 0-week control. The remaining rice was placed in quart (0.95 L) glass Mason jars and distributed among temperature-controlled storage units maintained at 10°C, 15°C, and 20°C. A walk-in cooler was used for the 10°C level. The 15°C level in 2014 and the 20°C level in both years were maintained in storage units that were coupled to temperature- and humidity-control units (AA5582, Parameter Generation and Control, Inc., Black Mountain, NC). In 2015, a cooling incubator was used as the 15°C storage unit (KB720, BINDER Inc., Bohemia, NY). The temperatures within each storage unit were verified by sensors (HOBO Pro v2, Onset Computer Corp., Bourne, MA) that recorded temperature every five minutes and remained in the units throughout the course of the study. Since the samples were contained in air-tight jars, the relative humidity within each unit was not controlled.

One jar of each cultivar/MC/temperature combination was removed at each of seven storage durations: 2, 4, 6, 8, 10, 12, and 16 weeks. As such, 56 jars (2 cultivars x 4 MCs x 7 storage durations) were placed in each of the three temperature-controlled storage units, representing a total of 168 jars for analysis each year. The storage conditions are summarized in Table 6. After a given storage duration, the MC of two, 15-g samples from each removed jar were measured by drying for 24 h in a 130°C oven, and the remaining rough rice was dried to 12.5% MC in a chamber with air conditions controlled at 27°C and 60% relative humidity by a temperature- and humidity-control unit (AA5582, Parameter Generation and Control, Inc., Black Mountain, NC). After drying, duplicate 150-g rough rice sub-samples from each jar were dehulled with an impeller husker (Model FC2K, Yamamoto, Yamagata, Japan), then milled using a laboratory mill (McGill No. 2, RAPSCO, Brookshire, TX), having a 1.5-kg mass placed on the lever arm, 15 cm from the centerline of the milling compartment. In 2014, milling durations were 17 s for XL753 and 22 s for CL XL745; in 2015, milling durations were 32 s for XP760 and 34 s for CL XL745. These durations were selected to result in a head rice surface lipid content (SLC) of 0.4%. After milling, head rice—whole kernels and broken kernels at least ¾ the length of a whole kernel—was separated from broken kernels using a sizing device (Model 61, Grain Machinery Manufacturing Corp., Miami, FL). Head rice yield was calculated as a mass percentage of the original 150-g rough rice sample.

Head rice SLC was verified by a diode array near-infrared reflectance (NIR) analyzer (DA 7200, Perten instruments, SE-141 05 Huddinge, Sweden). The NIR analyzer also estimated head rice color on the L*a*b* scale, but these bulk-sample data were deemed insufficient for describing discoloration, and particularly kernel-to-kernel variability, in many samples. To quantify discoloration more completely, an image analysis system (WinSEEDLE Pro 2005a™, Regent Instruments Inc., Sainte-Foy, Quebec, Canada) was used, in which approximately 100 kernels of head rice were arranged on a 32 mm-thick acrylic tray (152 mm x 100 mm x 20 mm), which was placed on a flatbed scanner and imaged with a blue background. The software analyzed the projected area of the kernels and quantified the percent of the kernel area that was occupied by pixels of pre-set color values. These values were selected from a set of discolored kernels chosen from samples in this study. Nine different colors were established: translucent and opaque white, three shades of yellow, red/brown, brown/black, pink/red, and light pink. The total discoloration of the 100-kernel sub-sample was calculated as the sum of all of the non-white color percentages. Two, 100-kernel sub-samples were measured from one of the two head rice sub-samples produced from each jar of rice.

A viscometer (RVA Super 4, Newport Scientific, Warriewood, Australia) was used to conduct viscosity analyses. Approximately 15 g of head rice were ground into flour with a cyclone mill (3010-30, UDY, Fort Collins, CO) and the flour MC was measured by drying a 2.5-g sample at 130°C for 1 hour. Approximately 3 g of flour and 25 mL of deionized water, with exact quantities determined by the flour MC, were combined in an aluminum sample canister. The 12.5-min RVA cycle consisted of holding the flour-water slurry at 50°C for 1.5 min, heating at a rate of 12°C/min to 95°C, holding for 2.5 min, then cooling to 50°C at a rate of 12°C/min, while stirring and measuring viscosity continuously. The data output was in the form of a curve, showing viscosity over the cycle duration, as well as summary values of peak viscosity, trough viscosity, breakdown (peak-trough viscosity), final viscosity, and setback (final-peak viscosity) viscosities, peak time, and pasting temperature.

A multiple regression platform (JMP Pro release 12.0.1, SAS Institute Inc., Cary, NC) was used for analysis. The MCs measured after storage for each jar were used instead of the bulk lot MCs because they were considered more representative of actual storage MCs for individual samples. To create a multiple regression model for each response, categorical terms (cultivar-year, cultivar, or year) were added as fixed effects, and storage MC, temperature, and duration were entered as continuous variables with all interaction terms. Interactions between fixed and random effects were included for analysis of discoloration. Polynomial effects were evaluated in viscosity analyses due to a curvilinear effect of duration seen in plots of the data. Non-significant terms and interactions ($\alpha > 0.05$) were removed manually by backwards elimination if they were not contained in significant higher-order effects. Least square (LS) means of each response by cultivar-year were compared with Tukey's Honestly Significant Difference (HSD) test.

D. Results and Discussion

Head rice yield

Head rice yield was not affected by storage conditions. As indicated in Table 7, there were inherent differences in HRY among the cultivar lots. Data from XL753 in 2014 were excluded from analysis due to anomalous HRY reductions in rice conditioned to MCs of 19% and 12.5% that were attributed to unknown pre-storage factors. Head rice yield in CL XL745 was significantly affected by the harvest year, with mean HRY in 2015 being 56.9%, 3.8 percentage points (pp) greater than in 2014. This difference is common due to annual variability in weather and harvest conditions that can impact HRY. These results demonstrate that with cooling to ambient temperature conditions of 10-20°C, HRY is not likely to be impacted at any MC up to 21% in long-grain cultivars stored for up to 16 weeks.

Discoloration

Discoloration varied among cultivars and between years, with average levels greatest in XL753, followed by CL XL745 in 2014. CL XL745 and XP760 in 2015 were significantly less susceptible to discoloration due to storage conditions than either cultivar in 2014, but not significantly different from each other (Table 7). Discoloration increased with increasing storage MC, temperature, and duration (Figure 10). Cultivar differences were evaluated by analyzing a subset of the data including XL753 and CL XL745 in 2014. Harvest year differences were analyzed by subsetting the data to include only CL XL745 in 2014 and 2015. In both cases, interactions between either cultivar or year and storage conditions were evaluated to account for effects on the slopes of the effects of storage factors. An individual regression analysis for discoloration in XP760 in 2015 is not included, however, as only 35% (adjusted R^2) of the variation in this cultivar's data was explained by an initial model.

The data for the discolored percentage of kernel area was positively skewed, as the vast majority of samples were measured at very low levels of discoloration, with a much lesser frequency of samples measured at mid-to-high levels. Though no transformation of the data fully normalized the distribution of this response, transformation with a natural log function established normality in the residuals in analysis. Because of this log-level transformation, parameter estimates for storage conditions were interpreted as the percent change in discoloration per unit increase in storage conditions by the following standard formula:

$$\%\Delta(discolored\ kernel\ area\ \%) = 100 \times (e^{\beta} - 1)$$

Parameter estimates for first-order and greater effects including MC were multiplied by 0.01 in order to interpret these coefficients in terms of pp increases in storage MC.

In 2014, discoloration was significantly less in CL XL745 than in XL753 (Table 7). On average between cultivars, a 1°C increase in temperature increased discoloration by 2.9%, and a 1 pp increase in MC increased discoloration by 8.8%. Storage duration only affected discoloration in interaction with increasing MC and temperature. Because of significant two-way and three-way interactions of storage MC, temperature, and duration, the slopes of the individual storage conditions' effects increased as every other factor increased. CL XL745 in 2014 experienced greater percentage-wise increases in discoloration due to increasing MC, as compared to XL753. However, this resulted in lesser absolute increases in discoloration with increasing storage conditions in CL XL745 because of the lower baseline levels of discoloration in this cultivar. The cultivar differences may indicate genetic susceptibility to discoloration, or may be the result of unknown environmental factors that were partially determined by the cultivars' different growing locations.

Significant annual variability in discoloration in cultivar CL XL745, however, may indicate that genetic factors, if they contribute to susceptibility to discoloration, are superseded by environmental differences. When annual effects were analyzed by modeling discoloration in CL XL745 only, discoloration in 2014 was demonstrated to be significantly higher than in 2015. (Table 7). On average between harvest years, a 1°C increase in temperature increased discoloration by 1.4%, while a 1 pp increase in MC increased discoloration by 8.9%, and a 1 week increase in storage duration increased discoloration by 4.6% (Table 8). Interactions among storage conditions, though significant, typically increased discoloration by a fraction of a percent. In 2015 the percentage-wise effect of storage duration was greater than in 2014, but this effect translated to lesser absolute increases in discoloration over time due to the lower baseline levels of discoloration in 2015.

The image analysis system used in this study for quantifying discoloration has not been compared to current USDA grading standards that require a human eye to evaluate kernels. Therefore for determining maximum thresholds for storage MC, temperature, and duration, an arbitrary value of 8% discoloration (-2.53 after natural log transformation) was considered the greatest acceptable level. This level of discoloration according to the image analysis output is a very light yellow color occupying a partial area of some kernels, and a human inspector may be unlikely to perceive this dispersed, pale discoloration as heat damage in any single kernel of a sample.

With a maximum threshold of 8% discoloration, the cultivar and harvest year differences clearly present a difficulty for using this dataset to predict discoloration. Both CL XL745 and XP760 in 2015 could be stored at the maximum MC, temperature, and duration (21%, 20°C, and 16 weeks, respectively) without exceeding that level 8% discoloration. But neither CL XL745 nor XL753 in 2014 could be stored under those conditions without reaching an unacceptable level of kernel discoloration. Though storage at 21% MC for 16 weeks at 10°C instead of 20°C reduced discoloration in CL XL745 to acceptable levels, XL753 was still above the threshold under the same conditions. Only a reduction of XL753's storage MC to 16% kept discoloration below 8% for 16 weeks at 10°C.

Until the pre-harvest factors that influence discoloration are identified and understood, and the image analysis system approach is validated with USDA standards, it is difficult to recommend cooling rough rice at 21% MC for an extended period of time for all long-grain, hybrid cultivars. Reducing MC to below 19% prior to cool storage should, however, be sufficient for storage at 10°C for up to 16 weeks. Additional research on the factors influencing kernel discoloration during storage should include an evaluation of pre-harvest factors, such as weather conditions and fungal populations. It is also not known how pure-line cultivars compare to the hybrid cultivars considered here with respect to susceptibility to discoloration.

Functionality

Baseline viscosity levels varied by cultivar and harvest year (Table 7), though trends in viscosity parameters over storage duration were consistent among cultivars and between harvest years. All storage conditions were shown to significantly impact peak viscosity (Table 8), but the only significant interaction effect was between temperature and duration. Storage duration tended to increase peak viscosity, leading to a greater swelling or water-holding capacity as compared to fresh rice. Peak viscosity tended to increase with storage duration, though viscosity levels peaked and leveled off, or started to decline, after about 8 weeks of storage (Figure 11), therefore a quadratic effect of duration was included in the regression model. Increasing storage MC was correlated with decreased peak viscosities. Cooling fresh rice for temporary storage therefore limits the increases in peak viscosity during storage significantly, and this may not be a desirable effect depending on the intended subsequent processing.

After reaching peak viscosity, the flour-water paste decreases to a trough viscosity, before the starch granules reorganize and viscosity increases to a final plateau. Trough viscosity was not significantly affected by any storage conditions, therefore breakdown, which is the difference between the peak and trough viscosities and a measure of stability to shear stress, increased with increasing temperature and storage duration (Figure 12), much like peak viscosity. The opposite trend in breakdown with increasing temperature and duration was observed in multiple studies, however (Swamy et al., 1978; Sowbhagya and Bhattacharya, 2001; Kanlayakrit and Maweang, 2004). In this study, the increase in breakdown with increasing storage temperature and duration was consistent among cultivars, though the real significance of this effect should be considered with caution since it occurred because of peak viscosity trends, as trough viscosity was unaffected by storage conditions. Ultimately, however, breakdown values were least with storage at 10°C for 16 weeks.

Final viscosity, like peak viscosity, increased with increasing storage temperature and duration, but it also increased slightly with increasing MC in interaction with increasing storage duration (Table 8); final viscosity also tended to level off or decline after 8 weeks of storage (Figure 13). Setback, an important processing indicator associated with reduced stickiness in Cameron and Wang's study (2005), is the difference between final and peak viscosities. Setback decreased with increasing temperature and storage duration, and increased with MC, independently and in interaction with storage duration. Due to these trends, setback was maximum at 21% MC, 10°C, and 16 weeks of storage (Table 8, Figure 14). This may also be attributed to the fact that increases in final viscosity with increasing storage temperature and duration were considerably less than increases in peak viscosity (Table 8); therefore higher storage temperatures yielded lower setback after 16 weeks as compared to samples stored at cooling temperatures. Previous studies have documented increasing setback during storage due to greater increases in final viscosity as compared to peak viscosity (Swamy et al., 1978; Kanlayakrit and Maweang, 2004).

The viscosity properties of rice stored at high harvest MCs under cooling conditions of 10-15°C therefore differ significantly from properties of rice stored after drying at 20°C. Cool storage of fresh rice limited increases in peak viscosity over the storage duration and therefore prevented development of high water-holding capacity desired in aged rice. However, trough viscosity was unaffected by any storage conditions, so stability to shear stress as determined by low breakdown values was not adversely affected by cold storage. Increases in final viscosity over storage duration are not limited by cold storage to the same degree as increases in peak viscosity, so after up to 16 weeks at 10-15°C, maximum setback was achieved in rice stored at 21%. It is not yet known if these changes in functionality would be practically significant from a processing standpoint. Additionally, though pasting temperature and peak time were significantly affected by some storage conditions, the range of these responses were 3.4°C and 0.3 min, respectively, and less within cultivar-year subsets; any changes in pasting temperature and peak time due to storage conditions were not considered practically significant.

E. Conclusions

Further research is needed to understand the pre-harvest factors that influence susceptibility to discoloration during storage. Given the observed variability among cultivars, pure-line cultivars should be studied alongside hybrids under identical controlled conditions. This applicability of these results is somewhat limited by the fact that cooling storage bins would also have aeration built in, possibly mitigating the effects of respiration on rice quality. Nevertheless the results here may give an adequate picture of what could be expected in a farm-scale situation. At grain MCs above 22%, the need for frequent re-cooling and heavy insulation precludes the use of cooling for more than a few weeks (Maier and Navarro, 2002). The maximum MC of 21% used in this study may therefore be economically feasible for short-term storage. The costs of cooling, however, should be compared to the saved costs of pre-parboil drying, as well as the value of preventing kernel discoloration that leads to downgrading or rejection of rice at processing points.

As an evaluation of the potential for using grain cooling to preserve the quality of fresh rice for up to 16 weeks without drying, this study may provide some reassurance to farmers or processors considering the implementation of such practices. Head rice yield should not be adversely affected by cooling, nor should kernel color when the coolest temperatures are used for minimal periods of time before drying or parboiling. Though high-MC, low-temperature storage conditions do reduce aging effects on peak viscosity, these conditions produced minimum breakdown and maximum setback values. The effects of these functionality changes on cooking and parboiling quality ought to be examined in future research.

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G. Tables and Figures

Table 6. Overview of experimental design.

Cultivars – Harvest Years	**Moisture Content (%)**	**Temperature (°C)**	**Duration (weeks)**
XL753 – 2014	12.5	10	2
CL XL745 – 2014	16	15	4
CL XL745 – 2015	19	20	6
XP760 – 2015	21		8
			10
			12
			16

Table 7. Least square means for head rice yield, kernel discoloration, and viscosity properties by cultivar and year. Significant differences between means were tested by Tukey's HSD.

Parameter	Cultivar	Year	LS Mean		Std Error	95% CI
Head rice yield (%)	CL XL745	2014	53.2%	A	0.14%	53.0%, 53.5%
	CL XL745	2015	56.9%	B	0.14%	56.6%, 57.1%
	XP760	2015	55.1%	C	0.14%	54.8%, 55.4%
ln[Discolored Area (%)]	XL753	2014	-2.33	A	0.050	-2.43, -2.23
	CL XL745	2014	-3.05	B	0.050	-3.15, -2.95
	CL XL745	2015	-4.10	C	0.047	-4.20, -4.01
	XP760	2015	-4.05	C	0.048	-4.14, -3.96
Peak viscosity (cP)	XL753	2014	3283	A	12.7	3258, 3308
	CL XL745	2014	2823	D	12.8	2798, 2848
	CL XL745	2015	2974	B	12.9	2949, 3000
	XP760	2015	2869	C	12.7	2844, 2894
Trough viscosity (cP)	XL753	2014	1640	A	7.2	1626, 1654
	CL XL745	2014	1510	B	7.2	1496, 1525
	CL XL745	2015	1468	C	7.3	1453, 1482
	XP760	2015	1400	D	7.2	1386, 1414
Breakdown (cP)	XL753	2014	1643	A	9.5	1624, 1662
	CL XL745	2014	1313	D	9.5	1294, 1331
	CL XL745	2015	1507	B	9.6	1488, 1526
	XP760	2015	1469	C	9.5	1451, 1488
Final viscosity (cP)	XL753	2014	3075	A	8.1	3059, 3091
	CL XL745	2014	3024	B	8.1	3008, 3040
	CL XL745	2015	3059	A	8.2	3042, 3075
	XP760	2015	2863	C	8.1	2847, 2879
Setback (cP)	XL753	2014	-209	D	8.3	-225, -192
	CL XL745	2014	201	A	8.3	185, 217
	CL XL745	2015	84	B	8.4	68, 101
	XP760	2015	-6	C	8.3	-23, 10

Table 8. Multiple regression model parameter estimates, standard errors, P-values, and 95% confidence intervals. Cultivar-year factors are expanded to all levels in viscosity regression analyses, and continuous variables are centered by mean. The natural log of discolored kernel area was evaluated for cultivar effects in 2014, followed by an analysis for harvest year effects with cultivar CL XL745. Adjusted R^2 values are indicated below each Parameter label.

Parameter	Term	Estimate	Std Error	Prob<|t|	95% CI
ln[Discolored Area (%)]	Intercept	-4.62	0.14	<.0001	-4.89, -4.35
2014	745	-0.36	0.020	<.0001	-0.40, -0.32
79%	745*MC	2.61	0.60	<.0001	1.4, 3.8
	745*D	0.0071	0.0045	0.118	-0.0018, 0.016
	745*MC*D	0.41	0.13	0.0025	0.15, 0.68
	T	0.0288	0.0050	<.0001	0.019, 0.039
	MC	8.45	0.60	<.0001	7.3, 9.6
	T*MC	0.49	0.15	0.0011	0.2, 0.78
	D	0.0066	0.0045	0.1423	-0.0022, 0.015
	T*D	0.0021	0.0011	0.0527	0, 0.0043
	MC*D	0.87	0.13	<.0001	0.60, 1.1
	T*MC*D	0.066	0.033	0.0446	0.0016, 0.13
ln[Discolored Area (%)]	Intercept	-5.60	0.24	<.0001	-6.07, -5.14
CL XL745	2014	0.52	0.035	<.0001	0.45, 0.59
71%	2014*D	-0.034	0.0073	<.0001	-0.048, -0.02
	T	0.014	0.0085	0.0971	-0.0026, 0.031
	MC	8.49	1.06	<.0001	6.39, 10.59
	T*MC	0.32	0.26	0.2174	-0.19, 0.84
	D	0.045	0.0073	<.0001	0.031, 0.06
	T*D	0.0034	0.0018	0.0538	0, 0.0069
Peak viscosity (cP)	Intercept	2828	37.1	<.0001	2755.5, 2901.3
76%	753-14	295.8	9.8	<.0001	276.5, 315.1
	745-14	-164.5	9.8	<.0001	-183.7, -145.3
	745-15	-13.2	9.8	0.1811	-32.5, 6.2
	760-15	-118.1	9.8	<.0001	-137.3, -98.9
	T	12.6	1.4	<.0001	9.9, 15.3
	MC	-506.0	163.7	0.0021	-827.8, -184.1
	D	8.1	1.2	<.0001	5.9, 10.4
	T*D	1.3	0.28	<.0001	0.74, 1.8
	D^2	-1.1	0.23	<.0001	-1.5, -0.60
Breakdown (cP)	Intercept	1338	27.8	<.0001	1283.2, 1392.4
73%	753-14	160.3	7.3	<.0001	145.8, 174.7
	745-14	-170.5	7.3	<.0001	-184.9, -156.1
	745-15	23.9	7.4	0.0013	9.4, 38.4
	760-15	-13.7	7.3	0.0626	-28.1, 0.72
	T	11.4	1.04	<.0001	9.3, 13.4
	MC	-431.3	122.6	0.0005	-672.5, -190.2
	T*MC	61.4	29.9	0.0410	2.5, 120.2

Table 8 (Cont.)

Parameter	Term	Estimate	Std Error	Prob<|t|	95% CI
	D	6.9	0.87	<.0001	5.2, 8.6
	T*D	1.4	0.21	<.0001	1.0, 1.8
	D^2	-0.90	0.17	<.0001	-1.2, -0.56
Final viscosity (cP)	Intercept	2883	23.6	<.0001	2836.9, 2929.6
63%	753-14	69.6	6.2	<.0001	57.3, 81.8
	745-14	18.9	6.2	0.0026	6.7, 31.1
	745-15	53.5	6.3	<.0001	41.2, 65.8
	760-15	-141.9	6.2	<.0001	-154.1, -129.7
	T	5.5	0.88	<.0001	3.8, 7.3
	MC	10.8	104.1	0.9177	-193.9, 215.5
	D	5.1	0.74	<.0001	3.6, 6.5
	T*D	0.47	0.18	0.0073	0.13, 0.82
	MC*D	44.9	20.9	0.0321	3.9, 86.0
	D^2	-0.55	0.15	0.0002	-0.84, -0.26
Setback (cP)	Intercept	55	24.2	0.0243	7.1, 102.3
82%	753-14	-226.2	6.4	<.0001	-238.8, -213.6
	745-14	183.4	6.4	<.0001	170.8, 195.9
	745-15	66.7	6.4	<.0001	54.1, 79.3
	760-15	-23.9	6.4	0.0002	-36.4, -11.3
	T	-7.0	0.90	<.0001	-8.8, -5.2
	MC	516.1	106.9	<.0001	305.9, 726.3
	D	-3.1	0.75	<.0001	-4.5, -1.6
	T*D	-0.81	0.18	<.0001	-1.2, -0.45
	MC*D	57.6	21.4	0.0075	15.5, 99.8
	D^2	0.51	0.15	0.0007	0.22, 0.81

***** 753-14: XL753 in 2014; 745-14: CL XL745 in 2014; 745-15: CLXL745 in 2015; 760-15: XP760 in 2015; MC: moisture content (%); T: temperature (°C); D: storage duration (weeks)

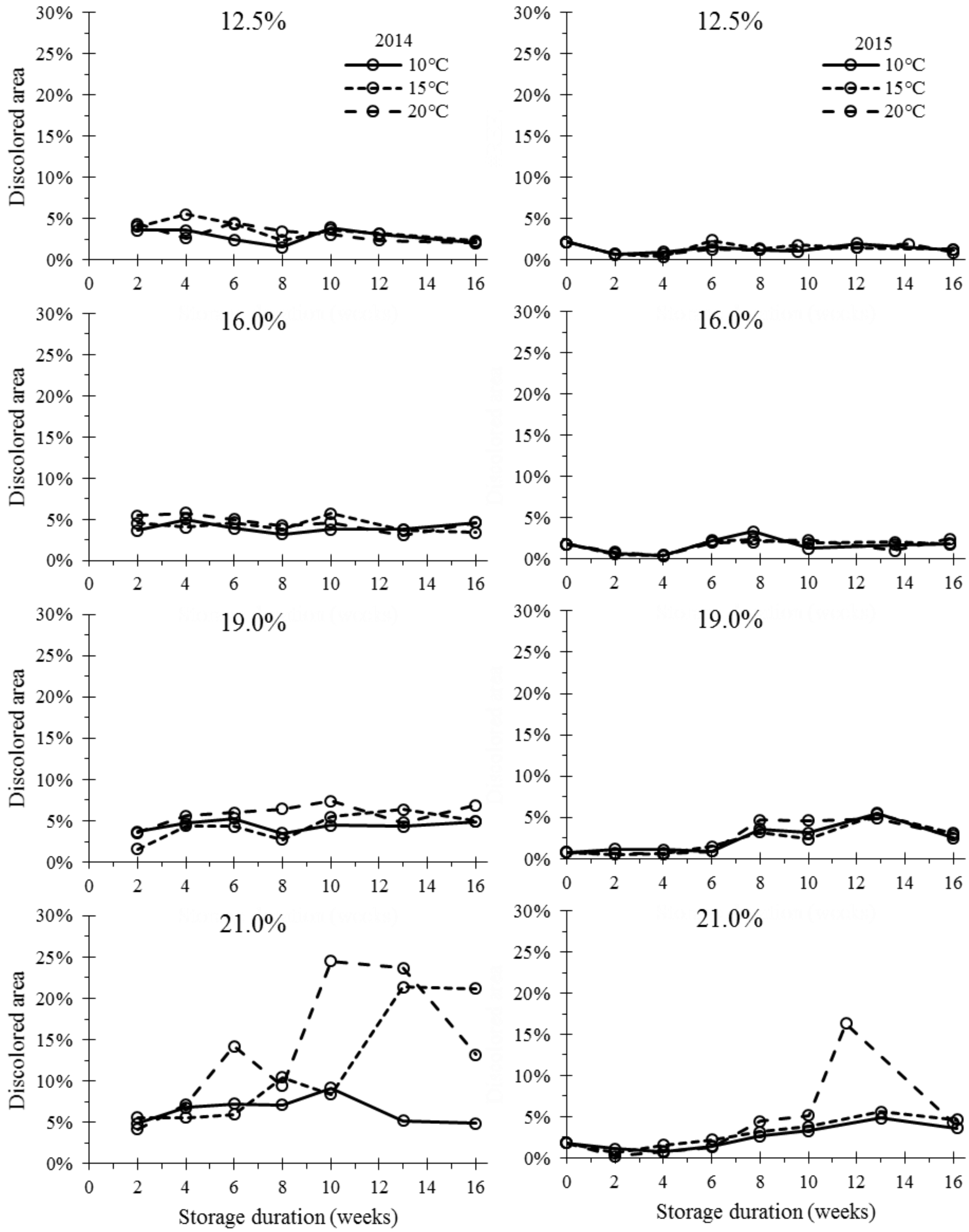

Figure 10. Changes in discolored kernel area of CL XL745 during storage at indicated moisture contents and temperatures in 2014 (left) and 2015 (right).

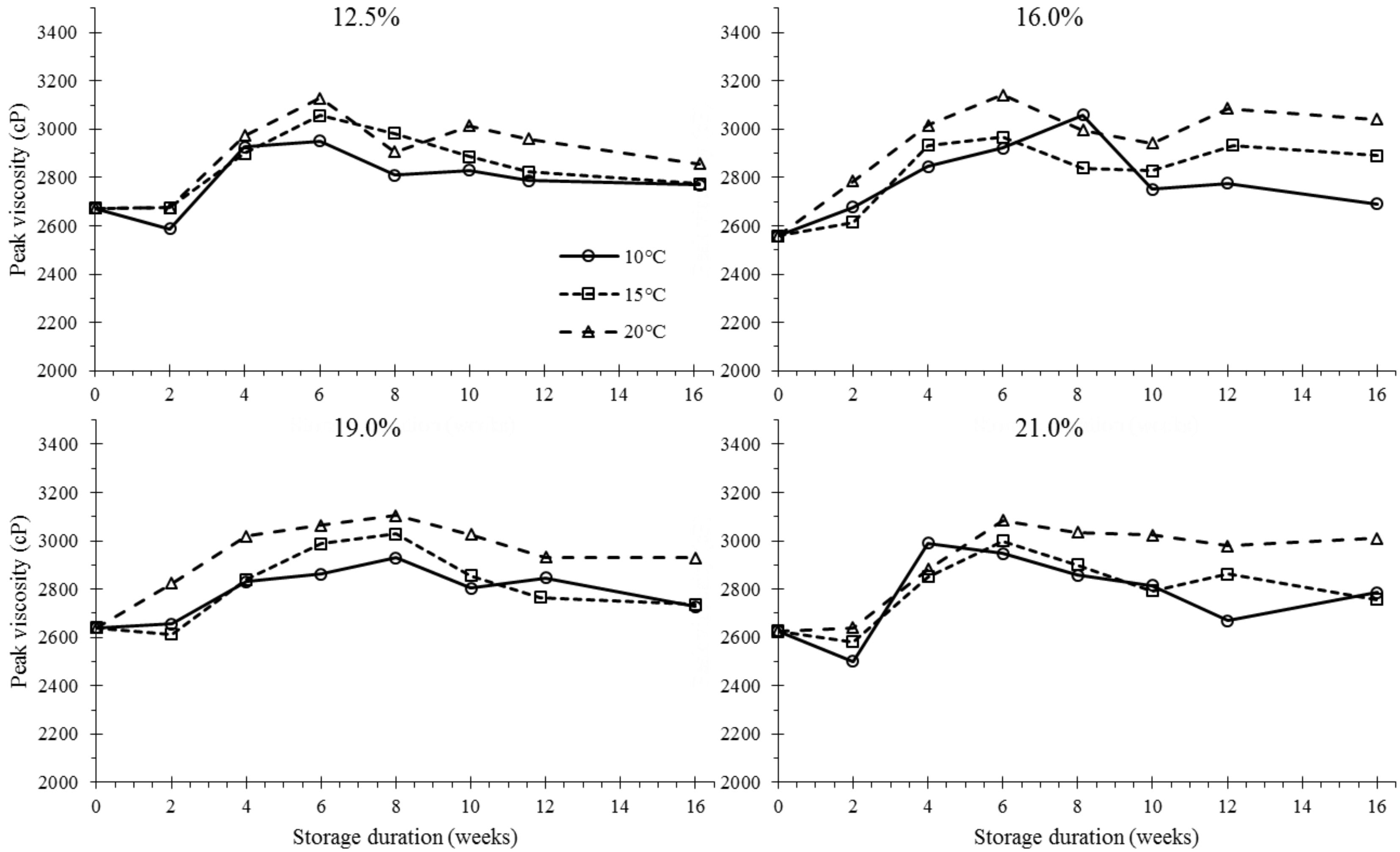

Figure 11. Changes in peak viscosity of cultivar XP760 during storage at indicated moisture contents and temperatures in 2015.

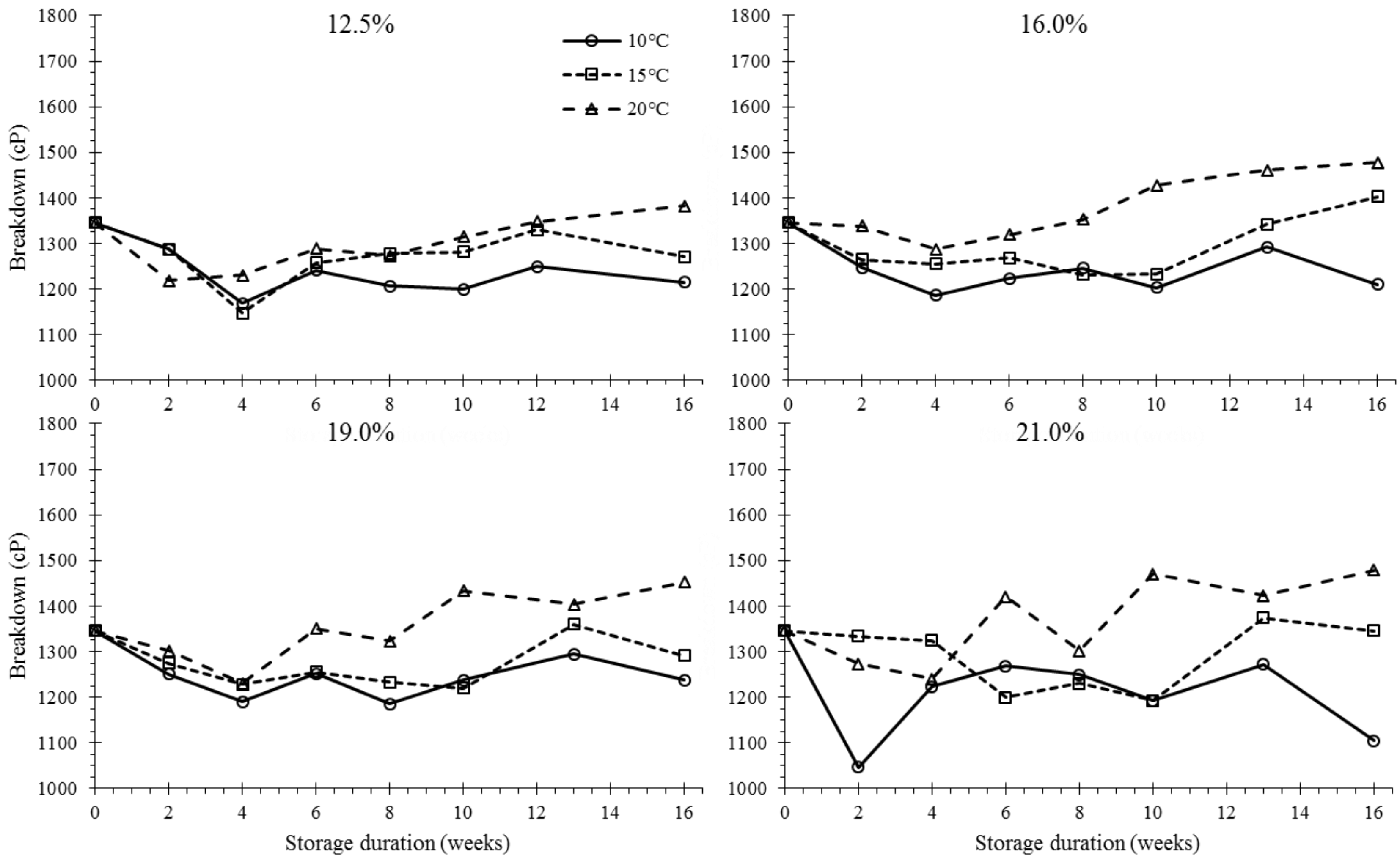

Figure 12. Changes in breakdown of cultivar CL XL745 during storage at indicated moisture contents and temperatures in 2014.

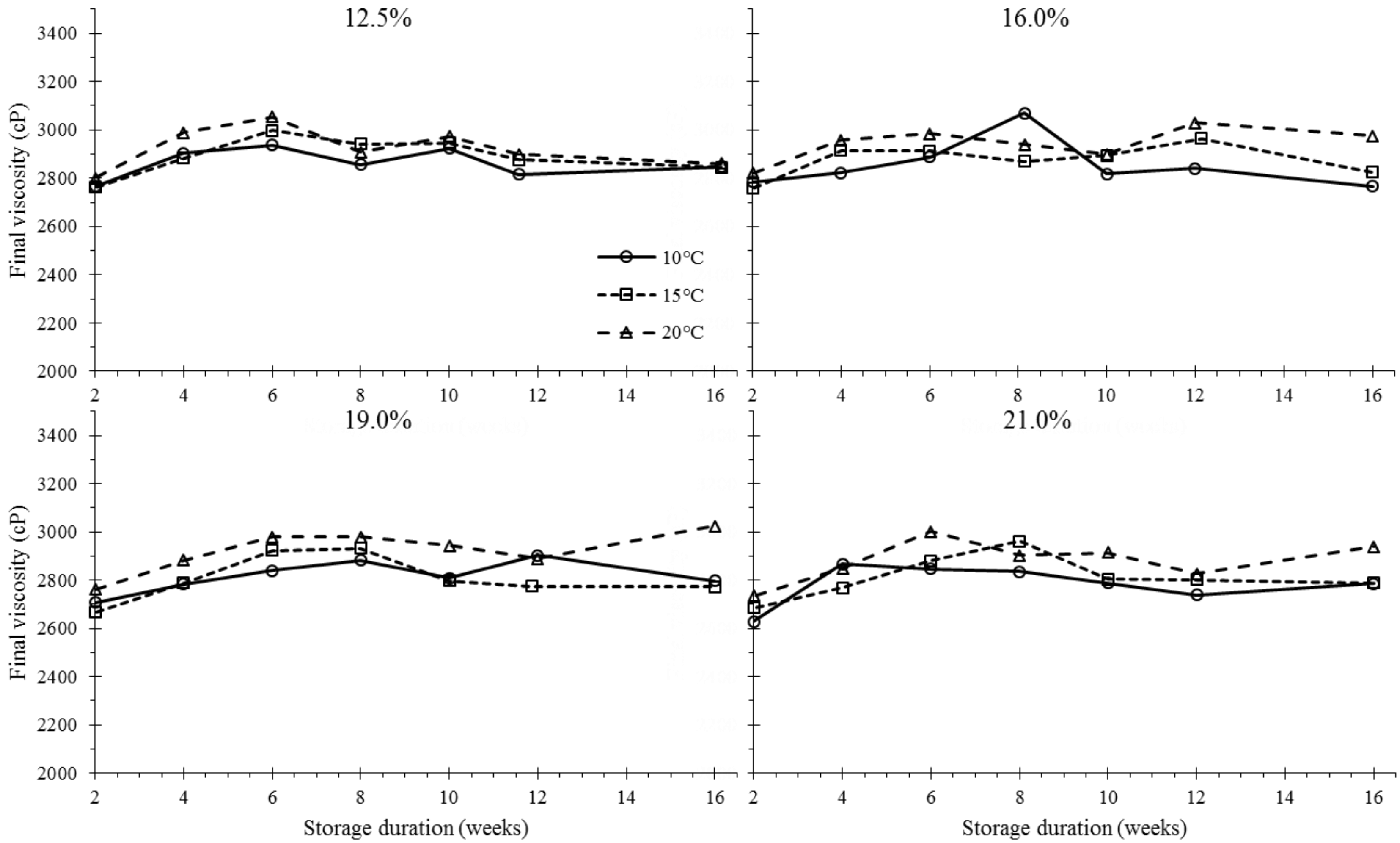

Figure 13. Changes in final viscosity of cultivar XP760 during storage at indicated moisture contents and temperatures in 2015.

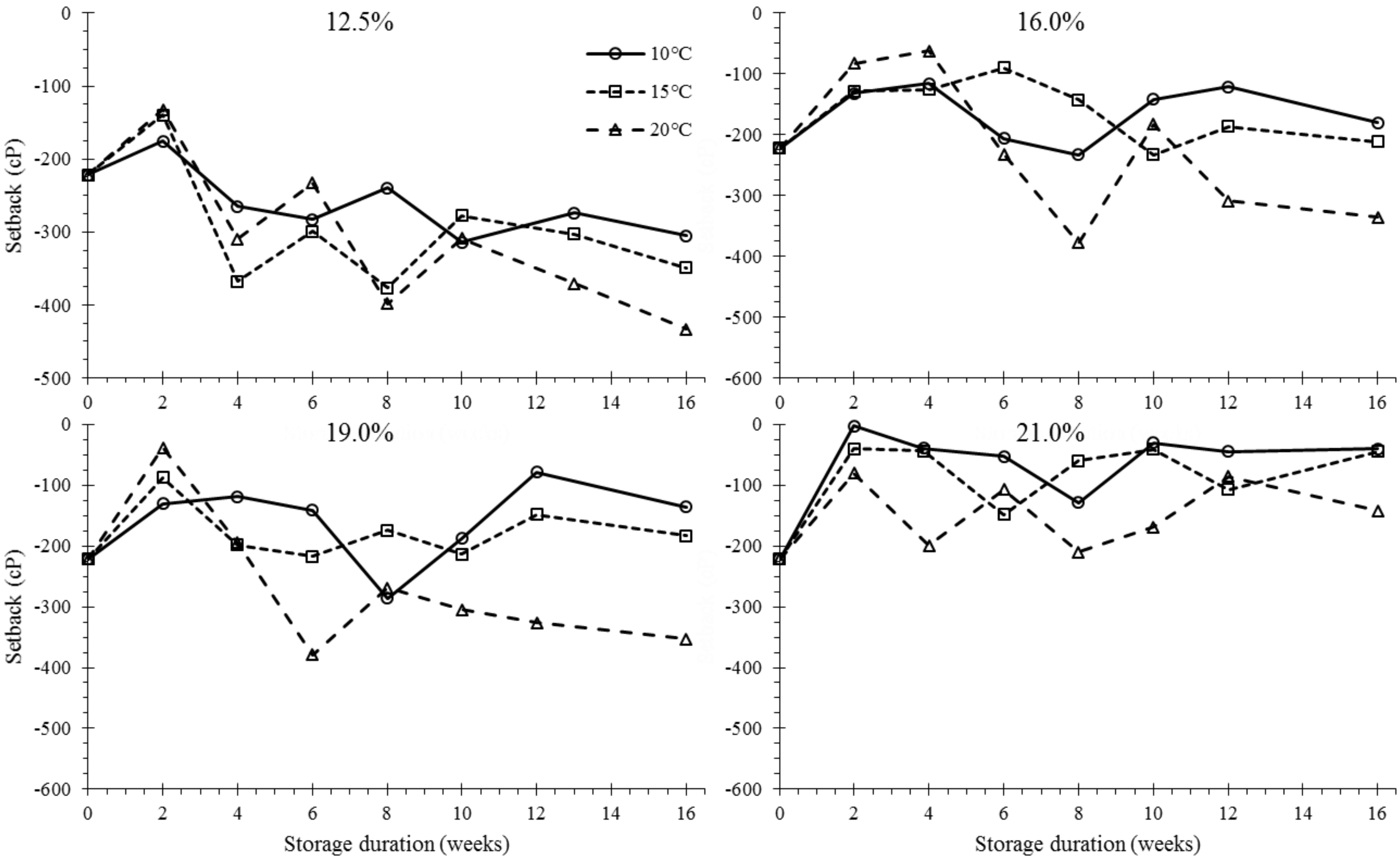

Figure 14. Changes in setback of cultivar XL753 during storage at indicated moisture contents and temperatures in 2014.

IV. Conclusions

This study included a broad range of temperatures, from grain cooling scenarios of 10-15°C to ambient temperatures typical in late summer to early autumn in the Mid-South United States, when rice is harvested. Moisture contents ranged from fully dried up to a harvest MC slightly above optimal levels for long-grain HRY returns. By sampling approximately every two weeks for nearly four months, HRYs, color changes, and functionality changes could be tracked closely, and then compared among cultivars and between harvest years. Though this study confirmed and corroborated findings by rice farmers and processors, it also lays a new foundation for other hypotheses to be explored, especially those related to discoloration. For users of in-bin dryers, these results model how quality can be affected without proper management of high-MC regions within bins. And for those curious about grain cooling for safe delayed drying, this study provides evidence of its potential costs and benefits.

Even with storage of high-MC rice at temperatures of 20-40°C, HRYs should not be negatively impacted until kernel discoloration and other quality reductions have occurred. Discoloration can set in within a few weeks, depending on MC and temperature, and even dried rice is susceptible to this process under certain temperatures. This discoloration is hypothesized to originate from two sources: fungi, which may be able to infect kernels and create black, brown, red, and pink pigments, and unknown biochemical changes due to storage MC, temperature, and duration interacting to promote the formation of yellow pigments.

If MC is properly controlled, storage can be used to positively impact functional properties. But storage at 40°C was shown to decrease starch peak viscosity after only 2-6 weeks. Maximum aging effects on peak viscosity can be attained by storing dried rice at or below 27°C for no more than 12 weeks, after which peak viscosity levels off or may begin to decline. Though cooling limits increases in peak viscosity, it does promote reduced breakdown and greater setback in long-grain cultivars. The impact of these effects on parboiling quality should be considered.

Cooling may provide a viable option for short-term preservation of high-MC rice, and is generally successful at preventing discoloration during storage, depending on the cultivar and circumstances of the specific harvest year. The costs of cooling should be weighed against the savings on drying prior to parboiling, and the potential value of virtually eliminating discoloration. Since HRY was also not impacted by cooling in this study, implementing such a practice could preserve and even enhance the quality of a farmer's rice. The overall results of this study can help guide current storage and drying practices, and promote the adoption of other quality-assurance techniques in the future.